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## SOLID STATE NEUTRON DETECTORS

JAMES F. MURPHY

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SOLID STATE NEUTRON DETECTORS

James F. Murphy  
//  
Lieutenant Commander  
United States Navy  
12 May 1961

Submitted in Partial Fulfillment of the Requirements for the Degree of  
Master of Science, U. S. Naval Postgraduate School, Monterey, California



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SOLID STATE NEUTRON DETECTORS

J. F. Murphy

ABSTRACT

Two methods of fabricating neutron detectors have been developed utilizing the principles of the solid state ionized particle detector. The  $(n,\alpha)$  reactions of  $\text{Li}^6$  and  $\text{B}^{10}$  are used for slow neutron detection. The Lithium and Boron are used as diffusants, for P and N type Silicon respectively, to create p-n junction diode detectors with efficiencies of the order of 1%. The fission of  $\text{U}^{235}$  is used for the detection of both slow and fast neutrons. The  $\text{U}^{235}$  is vacuum coated onto surface barrier detectors. Efficiencies of .004% have been obtained from these units in a thermal beam from the Livermore 2 MW pool-type reactor.

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# SOLID STATE NEUTRON DETECTORS

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## I. INTRODUCTION

The development of ionized particle detectors has received considerable attention during the past few years.<sup>1-6</sup> At the present time it is known that the Chalk River Laboratory,<sup>7</sup> the Lewis Research Center<sup>8</sup> and the Westinghouse Electric Corporation<sup>9</sup> are experimenting with ionized particle detectors which have been coated with neutron sensitive elements. This paper is concerned with the use of  $\text{Li}^6$  and  $\text{B}^{10}$  as diffusants to directly form silicon p-n junction neutron detectors and the use of uranium to form surface barrier neutron detectors.

Natural occurring lithium, an interstitial donor, has recently been used by Elliott<sup>6</sup> to form a p-n junction and to extend the depletion region with an ion drift process. A similar process for the separated isotope  $\text{Li}^6$  is discussed in the present paper. In this case neutron detection is accomplished with a  $\text{Li}^6 (n, \alpha) \text{T}$  reaction converting captured neutrons into charged particles, which in turn are detected within the depletion region. P-n junctions were also directly formed by a shallow diffusion of  $\text{B}^{10}$  (90-92% enriched) in N-type silicon. Here the  $\text{B}^{10} (n, \alpha) \text{Li}^7$  reaction formed ionized particles for neutron detection.

Additionally, neutron detection was investigated using the fission process in  $\text{U}^{238}$  and  $\text{U}^{235}$  for the conversion of fast and slow neutrons. In this case the restricted range of the highly ionized fission fragments required the use of surface barrier junction to detect the product charged particles. This was accomplished by vacuum coating uranium onto preformed gold surface barrier silicon diodes.

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Attempts were also made to form uranium surface barriers directly on silicon.

## II. GENERAL THEORY

### 1. Crystalline Structure.

All solids may be classified as crystals or non-crystals. A crystal is a structure which is produced by the repetition of a basic unit due to translation and is characterized by its extreme regularity. If this regularity or periodicity extends throughout the entire piece of material it is said to be a "single crystal". If the piece of material is an agglomerate of smaller crystallites, it is said to be "polycrystalline". In a non-crystal the atoms or atom groups are present in an irregular or random fashion. Examples of this type are super-cooled liquids, glasses and plastics (plastics sometimes exhibit a repetition of a basic unit but it is a spiral type structure, not translatable).

Crystals may be divided into seven crystal systems, fourteen space lattices, two hundred and thirty space groups and an infinite number of crystal structures. A complete discussion of these systems may be found in any basic solid state physics text.<sup>10</sup>

Silicon is an insulator with a valence of four. Like germanium it has a diamond structure in which each cell is composed of 8 atoms and each atom has 4 nearest neighbors. Strong bonds between the atoms result from a sharing or mutual exchange of electrons with its nearest neighbors. This type of binding is particularly stable and is called "covalent binding". This binding is of an electrostatic nature but can be explained only on a quantum mechanical basis utilizing what is known as exchange interaction.



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## 2. Band Structure

The complete theory on band structure is contained in any basic atomic physics text. Quantum mechanically the electron energy levels are determined by the quantum numbers. In a collection of atoms of the same type, the electron energy levels will separate into bands of energy levels. These bands have energy widths characteristics of the solid, but the number of levels within the band is determined only by the number of atoms present.  $N$  atoms provide  $N$  levels within each band. However, each level can accommodate two electrons because of spin. Therefore, a collection of  $N$  atoms lead to  $2N$  states within each band. In silicon and certain other diamond structures, there is a quantum mechanically forbidden zone between the valence and conduction bands. The conduction band is the lowest unfilled band at  $0^\circ\text{K}$ . The valence band is the next lower band. Metals contain an overlapping of bands so that no forbidden zone exists at these higher energy levels. In silicon this forbidden zone or gap occurs between the  $3s$  and  $3p$  shells and has an energy span of  $1.11\text{ eV}$ . In germanium the gap energy is  $.72\text{ eV}$  and it occurs between the  $4s$  and  $4p$  shells. Diamond on the other hand has a comparatively large gap energy,  $6\text{ eV}$ , and it is located between the  $2s$  and  $2p$  shells.

## 3. Fermi Levels

The location of the Fermi level determines the type of silicon (i.e. Intrinsic (I), Donor (N), or Acceptor (P)).

Intrinsic silicon contains no impurities. At  $0^\circ\text{K}$  there will be no electrons in the conduction band while the valence band will be full.





At any elevated temperature some states in the conduction band will be occupied by electrons while an equal number of vacant states will exist in the valence band. It can be shown that since the number of electrons in the conduction band and the number of vacant states in the valence band are a function of the Fermi probability function, there is a virtual Fermi face midway between the two bands.<sup>11</sup>

If a group V contaminant is introduced, the atoms of which are substituted for silicon atoms, there will exist one very loosely bound electron for each atom substituted. Only four of the contaminant's five valence electrons are required to complete the bonding with the silicon. To preserve charge neutrality the fifth electron must orbit the parent nucleus. The radius of the orbit is extended by the dielectric constant of the silicon. Since this fifth electron is loosely bound, it is easily excited into the conduction band of the silicon leaving the parent nucleus ionized. This process provides an excess number of electrons in the conduction band thus the Fermi probability function and consequently the Fermi face is shifted in the direction of the conduction band. Silicon containing a group V contaminant is called "donor" or "N" type.

If a group III contaminant is introduced substitutionally into silicon, there is a deficit of one bonding electron for each atom substituted. The vacant bond or hole can be thought of as an orbiting positive charge. Thermal excitation will fill this hole with a silicon valence electron thus transferring the hole to a silicon neighbor. The process of filling and transferring gives mobility to the hole.

The first difficulty arises from the fact that the  
 quantity of the commodity is not constant, but  
 it varies with the price of the commodity. It is  
 not a simple matter to find the price of the commodity  
 when the quantity of the commodity is not constant.  
 It is a problem of the theory of the value of money.

The second difficulty arises from the fact that the  
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 it varies with the price of the commodity. It is  
 not a simple matter to find the price of the commodity  
 when the quantity of the commodity is not constant.  
 It is a problem of the theory of the value of money.

The group III contaminant thus provides more holes in the valence band than there are electrons in the conduction band. The Fermi probability function and consequently the Fermi face resultantly shift in the direction of the valence band. In taking on the extra electron the contaminant takes on a negative charge. Silicon containing a group III contaminant is called "acceptor" or "P" type.

#### 4. Surface Barrier Junction

In a metal the atoms are held together with what is known as a "Metallic Bond". It can be thought of as a structure formed by positively charged metal ions embedded in a sea of mobile free electrons. In spite of the fact that the electrons move freely from atom to atom, charge neutrality is preserved. The Fermi level lies at the upper edge of the electron distribution within the partially filled valence band. If by some mechanism additional electrons are introduced into the valence band, the Fermi level will be raised and the metal will take on a net negative charge. This charge will appear as an infinitesimally thin sheet of charge on the surface of the metal. If, on the other hand, electrons are somehow drained from the valence band, the Fermi level is lowered and the metal takes on a net positive charge. This charge also appears as a thin sheet on the surface. In a semiconductor the situation is somewhat similar. In N type material the electrons in the conduction band are present as a result of excitations from the valence band and from ionization of the donor impurities. If the electrons are somehow drained from the conduction band, the Fermi level will be lowered and the semiconductor will take on a net positive charge. Unlike the metal, the charge in this case will be a distributed positive charge made up of the ionized donor atoms. Figure 1 shows





a metal and an N type semiconductor side by side, but not touching. In this case the work function ( $\phi_m$ ) of the metal is larger than the work function ( $\phi_s$ ) of the semiconductor. When the two are brought into contact, Figure 2, electrons will drain from the conduction band of the semiconductor and will be injected into the valence band of the metal until the two Fermi levels are at the same energy. The metal now has a thin negative surface charge while the semiconductor has a distributed positive charge or "Space Charge Region". An electric field is set up which is located entirely within the space charge region of the semiconductor. The height of the resulting potential barrier corresponds to the difference of the two work functions.

The current flow across the barrier is described in detail in the literature.<sup>10,11</sup> The total current is made up of four components, the electron flow from the metal to the semiconductor ( $I_a$ ), the electron flow from the semiconductor to the metal ( $I_b$ ), the hole flow from the metal to the semiconductor ( $I_c$ ), and the hole flow from the semiconductor to the metal ( $I_d$ ). See Figure 2. In equilibrium, an energy  $q(\phi_m - \phi_s)$  must be supplied to the electrons to enable them to cross the potential barrier.

Then  $I_a = -I_b = Ae^{-q(\phi_m - \phi_s)/kT}$ . The holes must be supplied energy in the amount of  $q\psi$  in order to cross the barrier. Then  $I_c = -I_d = Be^{-q\psi/kT}$ .

Under small forward and reverse voltage bias, the current components  $I_a$  and  $I_d$  will remain the same as for equilibrium conditions because the potential barrier they see does not change. However, the potential barrier as seen by components  $I_b$  and  $I_c$  does change. When a bias voltage ( $V_b$ ) is applied the Fermi level in the semiconductor is raised



or lowered depending on whether a forward or reverse bias is applied. The amount of energy necessary to be supplied to  $I_b$  electrons and  $I_c$  holes, under forward bias in order to cross the barrier, is reduced by the amount  $qV_b$ , from the equilibrium condition. Under reverse bias the opposite is true. When the Fermi level is raised under forward bias, it means that less electrons will be drained from the conduction band, hence less donors will be ionized and the space charge region will be narrower (Equation A-10). Conversely the space charge region will be increased under a reverse bias. In equation A-12 it is noted that the expression for capacitance is the same as for a parallel plate capacitor. In a parallel plate capacitor the capacitance varies directly with the area of the plates and inversely with the separation between them, while the charge appears as a thin sheet of charge on each plate. In a metal to semiconductor contact there is a thin sheet of charge on the metal but on the other plate which is the semiconductor there is a distributed space charge. Applying a reverse bias increases the width of the space charge region thus increasing the effective plate separation hence, decreasing the capacitance. The only other method of decreasing the capacitance is to physically reduce the area of the contact. The reduction of capacitance is important in detectors since the pulse height of the output pulse is inversely proportional to the capacitance.

By evaporating a thin coating of a metal onto N type silicon, assuming  $\phi_m$  is greater than  $\phi_s$ , a rectifying contact is made which under reverse bias becomes a detector for ionized particles.

When applying leads to a semiconductor device care must be taken





or a rectifying junction will occur where it is not desired. To obtain an ohmic (non-rectifying) junction between a metal and a semiconductor, the metal must be chosen such that its work function is smaller than that of the N type semiconductor. In this case the Fermi levels must once again line up. To accomplish this, electrons are drained from the valence band of the metal lowering its Fermi level. These electrons are injected into the conduction band of the semiconductor raising its Fermi level. Since there are many unoccupied states in the conduction band of the semiconductor there is no opposition to the flow of electrons in either direction, and there is no potential barrier set up. (Figure 3)

The analysis of the metal to P type semiconductor contact is similar to the one just carried out for the metal to N type semiconductor. To obtain a rectifying contact between a metal and P type semiconductor the metal must be chosen such that its work function is smaller than that of the semiconductor. To obtain an ohmic contact the work function of the metal must be greater than that of the semiconductor.

The solution of Poisson's equation for the case of the metal to semiconductor contact is contained in Appendix A. The charge distribution arises from the fact that there exists an abrupt change from high conductivity material to high resistivity material.



## 5. PN Junctions

The contact between two semiconductors of opposite type behave similar to that between a metal and a semiconductor. The Fermi level of the two semiconductors must again line up. To accomplish this electrons will drain from the N type semiconductor and be injected into the conduction band of the P type material. Holes will drain from the valence band of the P type semiconductor and be injected into the valence band of the N type material. This process equalizes the Fermi levels and creates a space charge region on both sides of the contact. The space charge region is composed of ionized donors and negatively charged acceptors in the N and P material respectively (Figure 4).

The current is again composed of four components and is described in detail in the literature.<sup>12,13</sup>  $I_a$  is the flow of electrons from the P to the N type semiconductor.  $I_b$  is the flow of electrons from the N to the P type semiconductor.  $I_c$  is the flow of holes from the P to the N type semiconductor and  $I_d$  is the flow of holes from the N to the P type semiconductor. In equilibrium,  $I_a = -I_b = Ae^{-q\psi/kT}$ , and  $I_c = -I_d = Be^{-q\psi/kT}$ . A and B are constant only for a constant temperature and they can be determined by solving the continuity equation and applying Fermi statistics<sup>11</sup>.

$$A = \frac{qD_n}{\sqrt{D_n \tau_n}} \cdot \frac{2(2\pi m k T)^{3/2}}{(h^2)}$$

$$B = \frac{qD_p}{\sqrt{D_p \tau_p}} \cdot \frac{2(2\pi m^* k T)^{3/2}}{(h^2)}$$

the first part of the paper, we shall consider the case in which

the function  $f(x)$  is continuous and the function  $g(x)$  is continuous.

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$$\frac{d}{dx} \left( \frac{f(x)}{g(x)} \right) = \frac{f'(x)g(x) - f(x)g'(x)}{g^2(x)}$$

$$\frac{d}{dx} \left( \frac{f(x)}{g(x)} \right) = \frac{f'(x)g(x) - f(x)g'(x)}{g^2(x)}$$



$q$  = Electronic charge

$D_n$  = Diffusion constant for electrons

$D_p$  = Diffusion constant for holes

$t_n$  = Minority carrier lifetime for electrons  
in P type material

$t_p$  = Minority carriers lifetime for holes  
in N type material

$m$  = Mass of the electron

$m^*$  = Effective mass of the hole

$k$  = Boltzmann's constant

$h$  = Plank's constant

$T$  = Temperature in degrees Kelvin

Under reverse bias  $I_b$  and  $I_c$  reduce to almost zero.

The total current flow then is the sum of  $I_a$  and  $I_d$  which is called the "saturation current". The sum of the widths of the two space charge regions, called the "Depletion region", is increased under reverse bias, equation B-2, and the capacitance is decreased, equation B-3. The charge distribution for this type of symmetrical junction is a graded distribution which may be approximated by a straight line. For the solution of Poisson's equation for a graded type junction see Appendix B. This symmetrical junction can be attained, practically, only in grown type junctions, where the concentration of dopants can be controlled so there is equal doping on both sides of the junction.

For diffused type junctions an extremely high concentration of dopant is located on one side of the junction and the contaminant distribution approaches a step function. As a result, the electric field and the depletion region are located mostly within the lightly doped side.



## 6. Detection of Ionized Particles

Energetic charged particles passing through a solid produce hole-electron pairs through interactions with the solid's electrons. These electrons, even from deep lying occupied bands, may be excited into unoccupied higher energy bands. The maximum energy that may be transferred to these electrons is  $E_{\max} = \frac{4mME}{(m+M)} \approx \frac{4mE}{M}$  where  $m$  is the mass of the electron and  $M$  and  $E$  are the mass and energy of the charged particles. For a 4 Mev alpha or a 1 Mev proton this is approximately 2 Kev of energy. On the average only 3.5 ev of energy is expended to produce an electron-hole pair in silicon.<sup>2,13</sup> It takes on the order of  $10^{-12}$  sec for the excited electrons to seek the lowest lying unoccupied band (conduction band) and for the holes to seek the highest occupied band (valence band). The hole and electron will then combine to complete the de-excitation with a characteristic time known as the "carrier lifetime". If these electron-hole pairs are produced within the depletion region they are rapidly swept aside and collected owing to the action of the electric field therein. If the electron-hole pairs are produced outside of the depletion region but within a diffusion length ( $L$ ), they will probably diffuse into the depletion region and be collected. Diffusion length ( $L$ ) is defined as  $L = \sqrt{Dt}$ , where  $D$  is the diffusion constant for holes or electrons as the case may be and  $t$  is the carrier lifetime. Electron-hole pairs created more than a diffusion length from the depletion region will recombine with their characteristic lifetime and not contribute to the output pulse.





Within the depletion region the clouds of electrons and holes pass each other so rapidly, owing to the action of the electric field, that very little recombination can take place. If however, certain impurities or crystal defects are present, trapping or recombination centers may be set up. A trapping center is a center in which a carrier may be temporarily trapped and then re-emitted. Carriers re-emitted from a trapping center cause a tail to form on the current pulse. A recombination center is a center in which a carrier may also be temporarily trapped but prior to re-emission a carrier of the opposite type is also trapped, in which case, the two carriers recombine. Recombination centers cause a degradation of the current pulse since less charges will be collected. The contribution of each carrier to the total charge is derived as follows:

$$m \frac{dv}{dt} = q \mathcal{E} \quad \text{or} \quad mv \frac{dv}{dt} = \frac{dE}{dt} = qv \mathcal{E} .$$

$\frac{dE}{dt}$  is the rate at which the electric field gives energy to the carrier, and  $q$ ,  $v$ , and  $m$  are charge, velocity and mass of the carrier. This energy comes from the junction capacitor which has  $\frac{Q^2}{2C}$  of energy stored.

Thus

$$\frac{dE}{dt} = \frac{d}{dt} \left( \frac{Q^2}{2C} \right) = \frac{Qi}{C} = V_c i = qv \mathcal{E}$$

$V_c$  is the total voltage across the capacitor. Then

$$i = \frac{dQ}{dt} = \frac{qv}{V_c} \mathcal{E} = \frac{q}{V_c} \quad \frac{dx}{dt} \frac{dV}{dx} = \frac{q}{V_c} \frac{dV}{dt} .$$

$\frac{dV}{dt}$  is the rate of change of the potential at the location of the carrier due to the carrier drift in the electric field. Finally

$$\int dQ = Q_{\text{eff}} = \frac{q}{V_c} \int dV = \frac{q \Delta V}{V_c}$$



where  $Q_{\text{eff}}$  is the effective charge at the electrodes due to the motion of one carrier through the fraction  $\frac{\Delta V}{V_c}$  of the total potential on the capacitor. Thus it can be seen that one carrier will contribute one charge  $q$  on making a complete passage across the capacitor. An electron-hole pair created between the plates of the capacitor will still only contribute one charge  $q$  since each carrier will contribute a fraction of the charge. The total charge ( $Q$ ) is equal to  $Q_{\text{eff}} N$ , where  $N$  is the number of hole-electron pairs liberated by a particle whose energy is  $E$ . If  $E$  is in Mev then

$$Q = \frac{Q_{\text{eff}} E}{3.5} \times 10^6 \text{ coulombs} \quad (1)$$

The charge collected is some fraction of the total charge available, because some of the hole-electron pairs are created more than a diffusion length from the depletion region while others are lost due to recombination within recombination centers.

The current pulse produced by the collection of the hole-electron pairs will have a rise time which is the carrier transit time ( $t_t$ ) across the depletion region.

$$t_t = \frac{d}{v_d} = \frac{d}{\mu} \mathcal{E}$$

$d$  is the width of the depletion region,  $v_d$  is the carrier drift velocity and  $\mu$  is the carrier mobility. These carrier transit times are typically of the order of nanoseconds. The carrier mobilities are functions of the impurity concentration and temperature. Typical values for mobility at room temperature for high resistivity silicon is  $\mu_n = 450 \text{ cm}^2/\text{volt-sec}$  and  $\mu_e = 1200 \text{ cm}^2/\text{volt-sec}$ . Curves of electron and hole mobilities as functions of the impurity concentration may be found in reference<sup>14</sup>.

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The ideal solid state detector should have rapid charge collection with an accompanying low loss of carriers. Rapid charge collection is attained through use of high resistivity material. High resistivity material has high carrier mobilities and in addition is capable of supporting large electric fields. The low loss of carriers is attained by having wide depletion regions which originate at the surface and freedom from recombination centers.





## 7. Neutron Detection

Neutrons, possessing no charge, can be detected only through secondary elastic or inelastic reactions.

### a. Elastic Reactions

Elastic collisions between fast neutrons and a hydrogenous material produce recoil protons. These protons can then be detected in the manner described in the previous section. Fast neutron detection devices might thus be fabricated merely by encapsulating the detector in plastic. No investigations were made using recoil proton counters. It is mentioned here in the interest of presenting a complete picture of possible solid state neutron detection devices.

### b. Inelastic Reactions

Vacuum coating p-n or surface barrier detectors with fissionable material presents a means of detection of both slow and fast neutrons. The fragments resulting from fission are highly ionized and possess high kinetic energies. These fragments are detectable as described in Section II-6, producing very large pulses.

Uranium was used as the fissionable material in this investigation. It was desired to check previous work where uranium was coated on preformed p-n junction detectors<sup>7,8</sup> and to compare these units with uranium coated surface barrier detectors.

As a first approximation the energy of the incident neutron may be neglected since the reaction energy for uranium is approximately 200 Mev. In this case the laboratory coordinate system will coincide with the center of mass coordinate system. The average mass of the two fission fragments of  $U^{235}$  are 97 and 139 amu.<sup>16</sup>

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$$T_L = \frac{M_H}{M_L + M_H} R = \frac{139}{236} 200 = 118 \text{ Mev}$$

$$T_H = \frac{M_L}{M_L + M_H} R = 82 \text{ Mev}$$

where  $T_L$  and  $M_L$  are the kinetic energy and mass of the light fragment and  $T_H$  and  $M_H$  are the kinetic energy and mass of the heavy fragment.

Many fissionable materials will not fission with slow neutrons. The neutron energy at which they commence to fission is called the "threshold energy". Some examples are<sup>17</sup>.

Isotope	Threshold Energy (Mev)	Cross Section at 2 Mev (Barns)
90 Th <sup>232</sup>	1.3	.11
91 Pa <sup>231</sup>	.5	1.05
92 U <sup>235</sup>	0	1.32
92 U <sup>236</sup>	1.0	.8
92 U <sup>238</sup>	1.0	.53
94 Pu <sup>239</sup>	0	2.0

If it is desired to detect only fast neutrons, one of the isotopes with a high threshold energy could be used for the detector coating. One difficulty arises from the fact that isotope separation is difficult for these high mass elements. A better method would be to use enriched U<sup>235</sup> for the detector coating and to use an absorber to selectively filter out the slow neutrons.

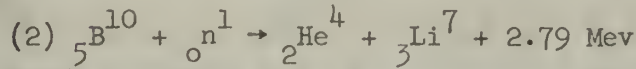
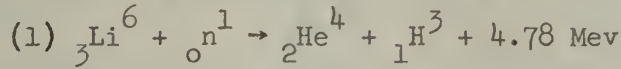
Slow neutrons may be detected by using (n,α) or (n,p) reactions. In general these are exoergic reactions. To determine the total charge which may be obtained equation 1 must be modified to include the reaction energy (R).



$$Q_T = \frac{Q_{\text{eff}} (E_n + R) \times 10^6}{3.5} \text{ coulombs} \quad (2)$$

where R is in Mev.

The two reactions used in this investigation are:



Both  $\text{Li}^6$  and  $\text{B}^{10}$  can be used as impurity diffusants to fabricate solid state neutron detectors. Lithium is a group I element. It acts as a donor since it diffuses interstitially. Boron is a group three acceptor.

The average thermal neutron energy ( $E_n$ ) is .025 ev. As a first approximation  $E_n$  can be neglected since  $E_n \ll R$ .

$$Q_T \approx \frac{Q_{\text{eff}} R \times 10^6}{3.5} \text{ coulombs} \quad (3)$$

Since  $E_n$  is neglected the laboratory coordinate system again coincides with the center of mass coordinate system. The kinetic energies of the reaction particles are:

$$T_1 = \frac{M_2}{M_1 + M_2} R \quad (4)$$

$$T_2 = \frac{M_1}{M_1 + M_2} R \quad (5)$$

$T_1$  and  $M_1$  are the kinetic energy and mass of the first reaction particle.  $T_2$  and  $M_2$  are the kinetic energy and mass of the second reaction particle. For reaction (1) and (2) the reaction particle energies are



(9)

$$\lim_{n \rightarrow \infty} \frac{f_n(x)}{g_n(x)} = \frac{f(x)}{g(x)}$$

where  $f, g$  are functions

defined on the interval  $[a, b]$  and  $f, g$  are continuous

$$\lim_{n \rightarrow \infty} f_n(x) = f(x) \quad \text{and} \quad \lim_{n \rightarrow \infty} g_n(x) = g(x) \quad (1)$$

$$\lim_{n \rightarrow \infty} \frac{f_n(x)}{g_n(x)} = \frac{f(x)}{g(x)} \quad (2)$$

where  $f, g$  are functions defined on the interval  $[a, b]$  and  $f, g$  are continuous. The limit (1) is called the limit of the sequence of functions  $f_n(x)$  and the limit (2) is called the limit of the sequence of functions  $\frac{f_n(x)}{g_n(x)}$ . The limit (1) is called the limit of the sequence of functions  $f_n(x)$  and the limit (2) is called the limit of the sequence of functions  $\frac{f_n(x)}{g_n(x)}$ .

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(10)

$$\lim_{n \rightarrow \infty} \frac{f_n(x)}{g_n(x)} = \frac{f(x)}{g(x)}$$

where  $f, g$  are functions defined on the interval  $[a, b]$  and  $f, g$  are continuous

defined on the interval  $[a, b]$  and  $f, g$  are continuous. The limit (1) is called the limit of the sequence of functions  $f_n(x)$  and the limit (2) is called the limit of the sequence of functions  $\frac{f_n(x)}{g_n(x)}$ .

(11)

$$\lim_{n \rightarrow \infty} \frac{f_n(x)}{g_n(x)} = \frac{f(x)}{g(x)}$$

(12)

$$\lim_{n \rightarrow \infty} \frac{f_n(x)}{g_n(x)} = \frac{f(x)}{g(x)}$$

where  $f, g$  are functions defined on the interval  $[a, b]$  and  $f, g$  are continuous. The limit (1) is called the limit of the sequence of functions  $f_n(x)$  and the limit (2) is called the limit of the sequence of functions  $\frac{f_n(x)}{g_n(x)}$ . The limit (1) is called the limit of the sequence of functions  $f_n(x)$  and the limit (2) is called the limit of the sequence of functions  $\frac{f_n(x)}{g_n(x)}$ .



Reaction	Particle	Kinetic Energy (Mev)
(1)	${}^4_2\text{He}$	2.05
(1)	${}^3_1\text{He}$	2.73
(2)	${}^4_2\text{He}$	1.78
(2)	${}^7_3\text{Li}$	1.01

The total charge ( $Q_T$ ) is independent of the angle of incidence of the neutron since the kinetic energy of the reaction particles is due almost entirely to the reaction energy (R).



### III. Preparation of Detectors

#### 1. Crystals

Diode preparation requires several mechanical operations common to both surface barrier and p-n types. See Figure 8. In all operations the utmost cleanliness must be observed because any contamination may ruin the detector. Between each operation the silicon must be thoroughly cleaned using only ultra high purity chemicals. A degreaser such as trichlorethylene should be used followed by an alcohol rinse followed by several rinses in distilled and deionized water. Handle the silicon only with clean tweezers to eliminate possible contamination with the hands.

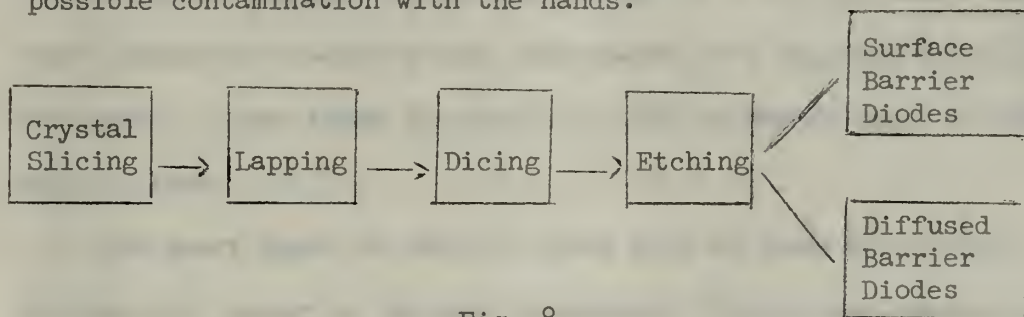


Fig. 8

Several silicon single crystals were purchased from the Merck Chemical Company. They are cylindrical in shape with diameters of approximately 20 mm and of various lengths between three and four inches. These crystals are high purity and thus high resistivity with resistivities ranging between 100 and 4000 ohm-cm of both N and P types.

Silicon is hard, brittle and chips easily. For this reason a high speed diamond saw must be used for slicing the crystal into circular discs (Fig. 9). The thickness of the disc is largely dependent upon the ultimate use of the detector (i.e. A  $d/dx$  detector must be thin so very little of the detected particles energy is lost in passing through the silicon.) If it is desired to use the



detector in a spectrometer, all of the detected particle's energy must be expended within the silicon and thus a fairly thick disc must be used. If it is desired to merely detect, almost any thickness may be used. A thickness of .030 inches was arbitrarily settled upon. Approximately .015 inches will be removed in subsequent operations.

During the slicing operation the silicon crystal must be held perfectly rigid. To do this the crystal is glued to a rectangular slab of porcelain using a resin pitch. The resin pitch was selected because it has good adhesive qualities, melts at a low temperature and is easily removed with alcohol (Fig. 9). The porcelain slab is then clamped in a metal holder and placed in a magnetic vice on the saw bench. A saw blade thickness of .020 inches is used to minimize silicon loss.

The scarf marks of the saw blade must be removed or uneven etching will occur in the next operation. These scarf marks are removed in a lapping process similar to that used for grinding glass.<sup>17</sup> A lucite mask containing six circular holes is placed between two stainless steel lapping blocks. The function of the mask is to contain the silicon slices, force the slices to slide over the lower lapping block and act as a limit so too much silicon will not be ground off. The upper block is driven by an eccentric mounted in the chuck of a slow speed drill press at 16 rpm. At this speed approximately .002 inches of silicon are removed per hour. A mixture of John Crane 1900 or 1950 lapping compound and water is used for the grinding compound. Stainless steel was used as the material for the lapping blocks since the water in the grinding compound would



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rust cast iron. Both faces of the silicon are lapped at the same time. The upper block (5" in diameter), driven by the eccentric, rotates against a lip on the mask (6" in diameter) thus forcing the mask, containing the silicon, to slide over the surface of the lower block (7" in diameter), which is stationary. A mask thickness of .020 inches was used. When the silicon slices are ground to a thickness of .020 inches, the mask, being the same thickness and relatively soft, inhibits further grinding. In this manner also, the two faces of the silicon discs are maintained very close to parallel.

Upon completion of lapping the silicon slices are diced to their final size. This size is determined by the amount of capacitance the ultimate system can tolerate and still get a good signal to noise ratio. Since the expression for capacitance is the same as that of a parallel plate capacitor eq. A-12, the capacitance varies directly with the first power of the area. As a result the smaller the area the smaller the capacitance and the larger the voltage signal. Most of the slices were diced into squares .200 inches on a side. To do this the silicon slices are once again mounted on the porcelain slab with the resin pitch but this time they are mounted in horizontal stacks to facilitate cutting.

The dicing operation may be deferred until after the diffusion operation. If it is, there exists the possibility of damaging the diffused surface due to increased handling but the sides will be free of the diffusant. If the dicing takes place at this point, any diffusion operation will also diffuse into the sides. This diffusant, however, may be removed by hand lapping or etching.

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Etching is a chemical means of polishing the silicon surface. The purpose is to expose any possible dislocations or other crystal-line imperfections, which would render the crystal useless. It also provides a smooth boundary from which diffusion can take place. To protect the reverse side during the etching process a mask of picein wax, dissolved in trichlorethylene, is applied. The volatile portions are then removed by placing the sample under an infrared lamp for 2 to 3 minutes. This leaves a hard wax coating which the acid will not attack and which is easily removed by again dissolving with trichlorethylene. The etch solution is a modified form of the standard CP-4 solution which contains:

	Parts by Volume
Concentrated Nitric Acid (70%)	3
Hydroflouric Acid (48%)	1
Glacial Acetic Acid	1

The nitric acid oxidizes the exposed silicon surface. The oxide formed is then removed by the action of the hydroflouric acid.

This reaction is fast ~~therefore~~ a buffering agent, the glacial acetic acid, must be used to make the reaction controllable. Dearnley and Whitehead<sup>4</sup> also recommend cooling the etch solution in an ice water bath as a further means of controlling the reaction.

During the etching process small bubbles form on the surface of the silicon. If they are not removed uneven etching will occur. These bubbles may be removed by agitating the silicon samples or by bubbling nitrogen gas through the etch solution. The latter is recommended.

Upon completion of etching the silicon must not be immediately exposed to air as this produces a brown discoloration on the silicon. Instead the etch solution must be diluted and decanted several





times before removal of the silicon to a beaker of distilled and deionized water where it is washed by diluting and decanting. The silicon is then dried by placing it in a stream of dry nitrogen gas. The silicon samples sometimes float to the surface of the etch solution where they become discolored. To avoid this the reverse side of the silicon should be attached to a piece of teflon or polyethylene, using the picein wax. The teflon or polyethylene will then act as an anchor to hold the samples below the surface. A fresh batch of etchant will produce a mirror finish in 4 to 5 minutes. An aged batch may take somewhat longer.





## 2. Surface Barrier Detectors

Surface barrier diodes are generally made from N type silicon because the difference between the thermionic work functions of most metals and that of silicon is generally greater for N type than it is for P type. This means that by using N type silicon for a base, larger barriers will be produced resulting also in a wider space charge regions. Care must be taken to ensure that the work function of the metal is **greater** than that of the N type silicon. If the work function of the metal is smaller than that of the N type silicon, an ohmic contact is made. The opposite holds true for the case of P type silicon.

For N type silicon a surface oxide layer provides an excellent barrier. After the etching process, the silicon sample is placed in a wet atmosphere for several hours, preferably over night, to form the barrier. After removal of the mask and a thorough cleaning the diodes are mounted. See Figure 10. Silver conducting paint is used to attach the base of the diode to the mounting and it also serves as one electrode. The other electrode is a .008 inch diameter stainless steel wire catwhisker.

Gold is generally evaporated onto the oxide surface to increase carrier collection efficiency. Dearnaley and Whitehead<sup>4</sup> prefer to evaporate the gold onto the freshly etched surface and allow the oxidation to take place through the gold. They believe this procedure protects the silicon from contamination.



### 3. Diffused P-N Detectors

Diffused devices are made in an open tube electric furnace (Fig. 11). The silicon samples are placed on a quartz holder and inserted into a quartz tube which passes through the furnace. The diffusant is passed through the tube by means of a carrier gas and deposited on the surface of the silicon samples from whence diffusion takes place. The concentration of the diffusant is such that the amount deposited on the silicon provides a maximum surface concentration regardless of time. An alternate method is to paint the diffusant onto the surface of the silicon. In either case a shallow diffusion is desired in order to place the depletion region as close to the surface as possible. To do this a relatively low temperature ( $900^{\circ}\text{C}$ ) and a short diffusion time (10 minutes) is used. At the end of this time the furnace is turned off and allowed to cool slowly. Fast cooling or quenching sets up recombination centers within the silicon which shortens the minority carrier lifetime, and which in turn degrades the output pulse. The slow cooling, on the other hand, allows the diffusant atoms to properly substitute for the silicon atoms in the lattice and thus reform a perfect crystal.

After the silicon is removed from the furnace the reverse face and the four sides are hand lapped or etched to remove all traces of the diffusant. The samples are then mounted as before.

The diffusion of impurities into the silicon is governed by Fick's second law which states that the rate of accumulation of the impurity at any point is proportional to the divergence of the gradient of the impurity. The constant of proportionality is the diffusion constant (D). Mathematically stated it is:

$$\frac{dN}{dt} = D \nabla^2 N$$





Solution of this equation is simplified in that it need only be solved for the x direction. The equation then becomes:

$$\frac{dN}{dt} = D \frac{\partial^2 N}{\partial x^2}$$

Two boundary conditions are necessary to completely solve the equation. The laboratory set-up was designed to provide a constant surface source therefore  $N(0,t) = N_s$ ,  $N_s$  is the surface concentration. The other boundary condition is a function of the distribution of the diffusant. In this case it is a step function.

$$\begin{aligned} N(x,0) = f(x) \qquad f(x) &= N_s \quad -\infty < x < 0 \\ &= 0 \quad 0 < x < \infty \end{aligned}$$

The solution of the equation is found in most texts on semiconductor technology.<sup>14</sup> The solution is:

$$\begin{aligned} N(x) &= N_s \left[ 1 - \frac{2}{\sqrt{\pi}} \int_0^{\frac{x}{2\sqrt{Dt}}} e^{-\lambda^2} d\lambda \right] \\ &= N_s \left[ 1 - \operatorname{erf} \frac{x}{2\sqrt{Dt}} \right] \\ &= N_s \operatorname{erfc} \frac{x}{2\sqrt{Dt}} \end{aligned}$$

Group V elements are used as diffusants to form PN junctions in P type material. Specifically the phosphorus pentoxide compound ( $P_2O_5$ ) was used. Its probable chemical reaction<sup>15</sup> is  $P_2O_5 + Si = P + \text{Phospho-silicate glass}$ . The  $P_2O_5$  is preheated to 225°C at which temperature it sublimates. The  $P_2O_5$  vapor is carried to the silicon in the furnace with a carrier gas of nitrogen. This nitrogen is

the first two terms of the expansion of  $\log(1+x)$  are  $x - \frac{x^2}{2}$ , and the third term is  $-\frac{x^3}{6}$ . The error in the approximation  $\log(1+x) \approx x - \frac{x^2}{2}$  is  $-\frac{x^3}{6}$ .

$$\log(1+x) = x - \frac{x^2}{2} + \frac{x^3}{6} - \frac{x^4}{24} + \dots$$

the first two terms of the expansion of  $\log(1-x)$  are  $-x - \frac{x^2}{2}$ , and the third term is  $-\frac{x^3}{6}$ . The error in the approximation  $\log(1-x) \approx -x - \frac{x^2}{2}$  is  $-\frac{x^3}{6}$ .

the first two terms of the expansion of  $\log(1+x^2)$  are  $x^2 - \frac{x^4}{2}$ , and the third term is  $-\frac{x^6}{6}$ . The error in the approximation  $\log(1+x^2) \approx x^2 - \frac{x^4}{2}$  is  $-\frac{x^6}{6}$ .

$$\log(1+x^2) = x^2 - \frac{x^4}{2} + \frac{x^6}{6} - \frac{x^8}{8} + \dots$$

the first two terms of the expansion of  $\log(1-x^2)$  are  $-x^2 - \frac{x^4}{2}$ , and the third term is  $-\frac{x^6}{6}$ . The error in the approximation  $\log(1-x^2) \approx -x^2 - \frac{x^4}{2}$  is  $-\frac{x^6}{6}$ .

$$\log(1+x^2) = x^2 - \frac{x^4}{2} + \frac{x^6}{6} - \frac{x^8}{8} + \dots$$

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obtained from the natural boil off from a dewar flask of liquid nitrogen.

Group III elements are used as diffusants to form PN junctions in N type silicon. Specifically two methods are used. First a suspension of Boron<sup>10</sup> in mineral oil is painted on the surface of the silicon. It is then heated to a temperature of about 250°C in a vacuum chamber to drive off the mineral oil. The boron coated pieces of silicon are then placed in the diffusion oven for the 10 minute diffusion. The second method is to drift boron trichloride gas ( $\text{BCl}_3$ ) over the silicon in the diffusion furnace. Its probable chemical reaction<sup>15</sup> is  $4\text{BCl}_3 + 3\text{Si} = 4\text{B} + 3\text{SiCl}_4$ .

The first part of the paper is devoted to a general discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one. The second part of the paper is devoted to a detailed discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one. The third part of the paper is devoted to a detailed discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one. The fourth part of the paper is devoted to a detailed discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one. The fifth part of the paper is devoted to a detailed discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one. The sixth part of the paper is devoted to a detailed discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one. The seventh part of the paper is devoted to a detailed discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one. The eighth part of the paper is devoted to a detailed discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one. The ninth part of the paper is devoted to a detailed discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one. The tenth part of the paper is devoted to a detailed discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one.

#### IV. EXPERIMENTAL UNITS AND RESULTS

##### 1. Uranium Detectors.

###### a. Preparation of Experimental Units.

Eight experimental detectors were prepared from 100 ohm-cm N type silicon as described in section III. Two detectors were given initial shallow diffused p-n junctions (barrier depth .07 microns) using boron trichloride in the open tube electric furnace. Four units were given oxide coatings by exposure to a wet atmosphere overnight. Two of the oxide units were then coated with 5000 Å of gold. The final two units were freshly etched. All eight units were placed in the slotted holders (Fig. 5) and placed in the vacuum chamber (Fig. 7). Uranium-235 was evaporated from the spread tungsten filament (Fig. 6) in an initial vacuum of  $5 \times 10^{-7}$  mm of Hg. An area of .08 cm<sup>2</sup> was exposed on each unit. Upon completion of the uranium evaporation, the units were mounted (Fig. 10) and sprayed with an acrylic plastic.

Uranium is extremely difficult to evaporate. Preliminary investigations using tantalum, molybdenum and carbon vessels showed that uranium went into solution with these materials at elevated temperatures (about 1000° C). The only material that uranium would not go into solution with was tungsten. When the uranium melts it partially wets the tungsten forming a ball of molten uranium around the filament. An oxide crust forms on the surface of the ball which inhibits evaporation until temperatures of about 2200° C are reached. Unfortunately this ball generally migrates to one end of the filament thereby causing coatings of different thickness to be deposited on the silicon units. Since uranium is a metal,

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the molten ball forms a conducting path with subsequent local cooling. The adjacent portions of the filament must then be excessively heated to provide sufficient heat for the evaporation. Another problem encountered was filament breakage before evaporation was complete. Initially .3 gram of uranium was placed on the filament. From past experience it was expected that about a 1 micron thick coating would be deposited on the silicon giving a thermal neutron efficiency of .3%.

The diode characteristics (Figures 14 to 17) were measured on a Tektronix 575 transistor curve tracer.

b. Results.

The uranium coated boron diffused units would detect neither the alpha decay of the  $U^{235}$  nor the fission fragments resulting from thermal neutron irradiation. It is believed this was caused by the poor diode characteristics of these units.

The uranium coated freshly etched units and surface oxide units would self count and also count fission fragments but their counting rate was extremely poor. Their counting efficiency for thermal neutrons was on the order of .0005%.

The uranium and gold coated surface oxide units were the best of the units tested. The efficiency of these units to thermal neutrons was on the order of .004%. Figure 12 shows the spectrum obtained from the alpha decay of the  $U^{235}$ . Figure 13 shows the spectrum of the energies of the fission fragments obtained as the result of thermal neutron irradiation. It is interesting to note that this offers a simple method of obtaining the mass distribution of the

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fission fragments. The energies shown are only approximate and were obtained by scaling from the 4.58 Mev self count peak. The energies of the two peaks are approximately 40 Mev lower than was expected (Section II-7). This discrepancy can partially be explained by the fact that fission fragments are highly ionized and lose most of their energy in the initial part of their path, part of which is beyond a diffusion length from the depletion region. The alpha particles, however, lose most of their energy toward the end of their path thus they lose very little energy prior to entering the depletion region.



## 2. B<sup>10</sup> Detectors

### a. Preparation of Experimental Units.

Four experimental B<sup>10</sup> detectors were prepared, using 2000 ohm-cm N type silicon. Two units received an initial boron diffused p-n junction (.08 microns), using boron trichloride in the open tube electric furnace. They were subsequently painted with B<sup>10</sup> enriched 90-92% (amorphous in oil). The oil was driven off in a vacuum chamber by heating to 250° C for 10 minutes. The other two units were painted with the enriched B<sup>10</sup> directly on the freshly etched surface. The oil was removed in the same manner. All four units were then placed in the furnace at 900°C for 10 minutes. The four units were then mounted the same as the uranium detectors and sprayed with plastic. The diode characteristics are as shown in Figures 18 and 19.

### b. Results

The two units having the preformed p-n junctions did not operate as well as those that were given only the B<sup>10</sup>. Figures 20, 21 and 22 show the reaction particle energy spectra, to a 10<sup>6</sup> neutrons/cm<sup>2</sup> sec thermal neutron beam, for 0,5 and 10 volts reverse bias. The efficiency to thermal neutrons of the best of the four units was about 1.3%.



### 3. Li<sup>6</sup> Detectors

#### a. Preparation of Experimental Units.

Two experimental Li<sup>6</sup> detectors were prepared from 1000 ohm-cm P type silicon. Li<sup>6</sup> (amorphous in oil) was painted on the freshly etched silicon surface. These units were then placed in a vacuum chamber and heated at 250° C for 10 minutes to drive off the oil. The temperature was then raised to 450° C for 90 seconds to diffuse the lithium into the silicon producing a barrier depth of 154 microns. The units were then mounted.

#### b. Results

Figure 23 shows the reaction particle energy spectrum to a 10<sup>6</sup> neutrons/cm<sup>2</sup> sec thermal neutron beam. The maximum energy of the triton (2.73 Mev) is shown on Figure 23. By scaling this energy to the small peak, the large peak indicates an energy of 2.05 Mev, which is the energy expected of the alpha particle. The efficiency of these detectors to thermal neutrons is about .4%. The ratio of the efficiencies of the Li<sup>6</sup> and B<sup>10</sup> approximately reflects the ratio of their cross sections.

$$B^{10} \sigma_{n\alpha} - 4020 \text{ barns}$$

$$Li^6 \sigma_{n\alpha} - 950 \text{ barns}$$

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The University of Chicago is a private research university in Chicago, Illinois. It was founded in 1837 and is one of the oldest and most prominent universities in the United States. The university is known for its commitment to academic excellence and its diverse student body. It has a long history of producing leaders in various fields of study and has been a major center for research and scholarship for over a century.

CHICAGO

Chicago is a city with a rich cultural and historical heritage. It is home to many world-famous institutions, including the University of Chicago, the Art Institute of Chicago, and the Field Museum of Natural History. The city is also known for its vibrant arts scene, its diverse cuisine, and its status as a major financial and commercial hub. Chicago's skyline, with its iconic skyscrapers, is a testament to its architectural achievements and its position as a global leader in business and industry.

$$\frac{1}{2} \log \frac{1}{2} = -\frac{1}{2} \log 2$$



## V. ELECTRONICS

Figure 24 is a block diagram of the electronics test equipment. The heart of the system is a low noise pre-amplifier, designed by F. S. Goulding. A schematic diagram of an improved version of this pre-amplifier may be found in Reference 5, Figure 9. The 256 channel analyzer (Radiation Counting Laboratory) requires input pulses between 0 and 100 volts with .5 microsecond rise times. The linear amplifier (UCRL Kaifer) compliments the analyzer.

The detector pulse has a rise time on the order of nanoseconds. The pulse is then integrated in both the pre-amplifier (rise time .4 microseconds) and the linear amplifier (rise time .5 microseconds) before going to the analyzer. A .55 microsecond clipping line was installed between the pre-amplifier and the linear amplifier to eliminate the low frequency noise. It was noted that the reverse current characteristics of the detectors was a direct indication of the noise to be expected.



## VI. CONCLUSIONS

Additional research is necessary to improve the efficiency of these detectors. The  $B^{10}$  detectors appear to hold the most promise for the detection of slow neutrons owing to their large cross section and ease of fabrication. The use of a guard ring<sup>5</sup> on these detectors would greatly improve their diode characteristics thus enabling the use of larger reverse bias voltages.

Possible uses of these devices include: Space probe detection units; Reactor core flux mapping; Neutron beam collimation and exploration; Medical research; and Neutron spectroscopy.

the people of the United States, from the first settlement of the colonies to the present time, is a subject of great interest and importance. It is a subject which has attracted the attention of many of our most distinguished writers and historians. The history of the United States is a history of a people who have been able to overcome all the difficulties and obstacles which have been thrown in their way, and to establish a government which has been the envy of all other nations. The history of the United States is a history of a people who have been able to maintain their freedom and independence, and to preserve their rights and liberties, in the face of all the attacks and assaults which have been made upon them. The history of the United States is a history of a people who have been able to build up a great and powerful nation, and to make a name for themselves in the world. The history of the United States is a history of a people who have been able to do all these things, and more, in the face of all the difficulties and obstacles which have been thrown in their way. The history of the United States is a history of a people who have been able to overcome all the difficulties and obstacles which have been thrown in their way, and to establish a government which has been the envy of all other nations. The history of the United States is a history of a people who have been able to maintain their freedom and independence, and to preserve their rights and liberties, in the face of all the attacks and assaults which have been made upon them. The history of the United States is a history of a people who have been able to build up a great and powerful nation, and to make a name for themselves in the world. The history of the United States is a history of a people who have been able to do all these things, and more, in the face of all the difficulties and obstacles which have been thrown in their way.

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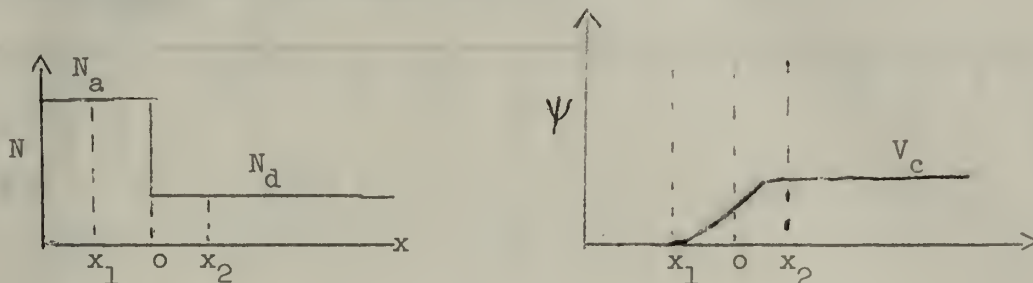
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# Appendix A

## Solution of Poisson's Equation for a Surface Barrier Junction..

An abrupt junction or shottky type barrier occurs when the semiconductor dopant changes abruptly from N to P type or vice versa in the relatively short distance of 1 to 2 atomic distances. This solution is applicable to surface barrier, alloyed and shallow diffused diodes.



The above two figures illustrate the dopant concentration ( $N$ ) and potential distribution in initially N type silicon with a P type surface concentration. For convenience the origin is considered at the point where the concentration changes.

$N_a$  = Acceptor surface concentration

$N_d$  = Donor concentration

$0-x_1$  = Width of the depletion region in the P type material

$x_2-0$  = Width of the depletion region in the N type material

$V_c$  = Voltage across the equivalent capacitor

$$V_c = V_B + \phi_a - \phi_d$$

$V_B$  = Reverse bias

$\phi_a$  = Fermi potential of the acceptor material

$\phi_d$  = Fermi potential of the donor material

# 1. Introduction

The purpose of this paper is to study the properties of the function  $f(x)$  defined by the equation  $f(x) = \int_0^x f(t) dt$ . It is well known that the only function satisfying this equation is the zero function. However, we will show that there are non-zero functions satisfying this equation if we allow  $f(x)$  to be a distribution. In the first section, we will define distributions and show that the equation  $f(x) = \int_0^x f(t) dt$  has non-zero solutions in the space of distributions. In the second section, we will study the properties of these solutions and show that they are all multiples of the Heaviside function  $H(x)$ .



In the third section, we will study the properties of the solutions of the equation  $f(x) = \int_0^x f(t) dt$  in the space of distributions. We will show that these solutions are all multiples of the Heaviside function  $H(x)$ . In the fourth section, we will study the properties of the solutions of the equation  $f(x) = \int_0^x f(t) dt$  in the space of distributions. We will show that these solutions are all multiples of the Heaviside function  $H(x)$ .

2. Distributions and the equation  $f(x) = \int_0^x f(t) dt$ . In this section, we will define distributions and show that the equation  $f(x) = \int_0^x f(t) dt$  has non-zero solutions in the space of distributions. We will define distributions as linear functionals on the space of test functions. We will show that the equation  $f(x) = \int_0^x f(t) dt$  has non-zero solutions in the space of distributions. We will show that these solutions are all multiples of the Heaviside function  $H(x)$ .

3. Properties of the solutions of the equation  $f(x) = \int_0^x f(t) dt$  in the space of distributions. In this section, we will study the properties of the solutions of the equation  $f(x) = \int_0^x f(t) dt$  in the space of distributions. We will show that these solutions are all multiples of the Heaviside function  $H(x)$ . We will show that the solutions are all multiples of the Heaviside function  $H(x)$ .

The boundary conditions taken from the figures are:

$$\left. \frac{d\psi_a}{dx} \right|_{x=x_1} = 0 \quad \left. \frac{d\psi_d}{dx} \right|_{x=x_2} = 0$$

$$\left. \psi_a \right|_{x=x_1} = 0 \quad \left. \psi_d \right|_{x=x_2} = V_c$$

$\psi$  and  $\frac{d\psi}{dx}$  are continuous at  $x = 0$

---

$$\nabla \cdot D = \rho$$

$$D = \epsilon E$$

$$E = -\nabla \psi$$

$$\therefore \nabla^2 \psi = -\frac{\rho}{\epsilon}$$

$$\rho_a = -q(N_a + n - p)$$

$n$  = electron concentration

$p$  = hole concentration

Assume  $N_a \gg (n - p)$

$$\therefore \rho_a = -q N_a$$

$q$  = electronic charge

$$\text{also } \rho_d = +q N_d$$

$$\nabla^2 \psi_a = \frac{q N_a}{\epsilon}$$

All the  $y$  and  $z$  donations drop out since the junction is in the  $y z$  plane.

$$\text{then } \frac{d^2 \psi_a}{dx^2} = \frac{q N_a}{\epsilon}$$

$$\left. \frac{d\psi_a}{dx} \right|_{x_1}^x = \frac{q N_a}{\epsilon} x \left|_{x_1}^x\right.$$

$$\frac{d\psi_a}{dx} = \frac{q N_a}{\epsilon} (x - x_1) \quad (A-1)$$



... ..

$$= \int_0^1 \frac{1}{x} dx$$

$$= \ln x \Big|_0^1$$

$$= \int_0^1 \frac{1}{x} dx$$

$$= \ln x \Big|_0^1$$

$$= \ln 1 - \lim_{x \rightarrow 0^+} \ln x = 0 - (-\infty) = \infty$$

$$f(x) = \frac{1}{x}$$

$$f'(x) = -\frac{1}{x^2}$$

$$f''(x) = \frac{2}{x^3}$$

$$f'''(x) = -\frac{6}{x^4}$$

$$(f(x) - f(a)) - f'(a)(x-a) = \frac{1}{x} - \frac{1}{a}$$

$$= \frac{1}{x} - \frac{1}{a} = \frac{a-x}{ax}$$

$$= \frac{a-x}{ax}$$

$$= \frac{a-x}{ax}$$

$$f(x) = \frac{1}{x}$$

$$f'(x) = -\frac{1}{x^2}$$

$$f''(x) = \frac{2}{x^3}$$

$$f'''(x) = -\frac{6}{x^4}$$

... ..

$$\frac{f(x)}{g(x)} = \frac{f'(x)}{g'(x)}$$

$$\int \frac{f(x)}{g(x)} dx = \int \frac{f'(x)}{g'(x)} dx$$

$$(f(x) - f(a)) - f'(a)(x-a)$$

$$= \frac{f(x)}{g(x)} - \frac{f'(x)}{g'(x)} = \frac{f(x)g'(x) - f'(x)g(x)}{g(x)g'(x)}$$



$$\psi_a \Big|_{x_1}^x = \frac{q N_a}{\epsilon} \left( \frac{x^2}{2} - x_1 x \right) \Big|_{x_1}^x$$

$$\psi_a = \frac{q N_a}{2 \epsilon} (x^2 - 2 x_1 x + x_1^2)$$

$$\psi_a = \frac{q N_a}{2 \epsilon} (x - x_1)^2 \quad (A-2)$$

The solution for the acceptor region follows the same method.

$$\frac{d\psi_a}{dx} = - \frac{q N_d}{\epsilon} (x - x_2) \quad (A-3)$$

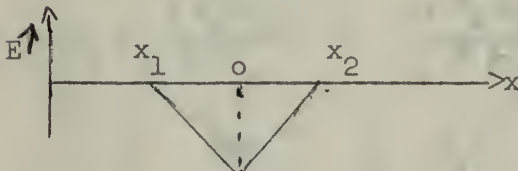
$$\psi_d \Big|_{x_2}^x = - \frac{q N_d}{2 \epsilon} (x^2 - 2 x_2 x) \Big|_{x_2}^x$$

$$\psi_d = v_c - \frac{q N_d}{2 \epsilon} (x - x_2)^2 \quad (A-4)$$

From equations A-1 and A-3 the electric field is :

$$E_a = - \frac{q N_a}{\epsilon} (x - x_1) \quad (A-5)$$

$$E_d = + \frac{q N_d}{\epsilon} (x - x_2) \quad (A-6)$$



at  $x = 0$   $\frac{d\psi_a}{dx} = \frac{d\psi_d}{dx}$

$$\begin{aligned} \frac{q}{\epsilon} N_a (0 - x_1) &= - \frac{q}{\epsilon} N_d (0 - x_2) \\ &= \frac{q}{\epsilon} N_d (x_2 - 0) \end{aligned}$$

$(0 - x_1) = d_a$  = depletion region in the P material

$(x_2 - 0) = d_d$  = depletion region in the N material

$$d_a = \frac{N_d}{N_a} d_d \quad (A-7)$$

$$\int (x^2 + 3x + \frac{4}{x}) dx$$

$$\int (x^2 + 3x + \frac{4}{x}) dx = \frac{x^3}{3} + \frac{3x^2}{2} + 4 \ln|x| + C$$

$$(1-1) \quad \int (x^2 - 3x + \frac{4}{x}) dx = \frac{x^3}{3} - \frac{3x^2}{2} + 4 \ln|x| + C$$

Section 7.1: Integration of Functions of the Form  $f(x) = ax^p$

$$(1-1) \quad \int x^p dx = \frac{x^{p+1}}{p+1} + C \quad (p \neq -1)$$

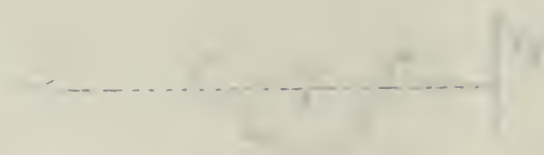
$$(1-2) \quad \int \frac{1}{x} dx = \ln|x| + C$$

$$(1-3) \quad \int x^{-1} dx = \ln|x| + C$$

Section 7.2: Integration of Functions of the Form  $f(x) = e^{ax}$

$$(1-4) \quad \int e^{ax} dx = \frac{e^{ax}}{a} + C \quad (a \neq 0)$$

$$(1-5) \quad \int e^{-ax} dx = -\frac{e^{-ax}}{a} + C \quad (a \neq 0)$$



$$\frac{d}{dx} e^{ax} = a e^{ax}$$

$$(1-6) \quad \int e^{ax} dx = \frac{e^{ax}}{a} + C$$

$$(1-7) \quad \int e^{-ax} dx = -\frac{e^{-ax}}{a} + C$$

Section 7.3: Integration of Functions of the Form  $f(x) = \sin(ax)$

Section 7.4: Integration of Functions of the Form  $f(x) = \cos(ax)$

Equation (A-7) shows that for equal concentrations the depletion region on each side of the barrier is equal. Realistically this does not occur. For high resistivity material ( $N_d \ll N_a$ ) the depletion region approaches zero on the acceptor side hence the entire electric field is located on the donor side.

The total depletion region ( $d$ ) is

$$\begin{aligned} d &= d_a + d_d \\ &= \frac{N_d}{N_a} d_d + d_d \\ d &= \left( 1 + \frac{N_d}{N_a} \right) d_d \end{aligned} \quad (A-8)$$

at  $x = 0 \quad \psi_a = \psi_d$

$$\frac{q N_a}{2 \epsilon} (d_a)^2 = V_c - \frac{q N_d}{2 \epsilon} (-d_d)^2$$

$$\frac{q N_a}{2 \epsilon} \left( \frac{N_d}{N_a} d_d \right)^2 = V_c - \frac{q N_d}{2 \epsilon} d_d^2$$

$$V_c = \frac{q N_d^2 d_d^2}{2 \epsilon N_a} + \frac{q N_d d_d^2}{2 \epsilon}$$

$$= d_d^2 \frac{q N_d}{2 \epsilon} \left[ 1 + \frac{N_d}{N_a} \right]$$

$$d_d = \left[ \frac{2 \epsilon V_c}{q N_d \left( 1 + \frac{N_d}{N_a} \right)} \right]^{\frac{1}{2}} \quad (A-9)$$

Combining (A-8) and (A-9)

$$d = \left[ \frac{2 \epsilon V_c \left( 1 + \frac{N_d}{N_a} \right)}{q N_d} \right]^{\frac{1}{2}} \quad (A-10)$$

(1)  $f(x)$  is a function of  $x$  and  $y$  is a function of  $x$ .  
 (2)  $f(x)$  is a function of  $x$  and  $y$  is a function of  $x$ .  
 (3)  $f(x)$  is a function of  $x$  and  $y$  is a function of  $x$ .  
 (4)  $f(x)$  is a function of  $x$  and  $y$  is a function of  $x$ .

$$f(x) = \frac{1}{x^2} + \frac{1}{x^3}$$

$$f(x) = \frac{1}{x^2} + \frac{1}{x^3}$$

(1)

$$f(x) = \frac{1}{x^2} + \frac{1}{x^3}$$

$$f(x) = \frac{1}{x^2} + \frac{1}{x^3}$$

$$f(x) = \frac{1}{x^2} + \frac{1}{x^3}$$

$$f(x) = \frac{1}{x^2} + \frac{1}{x^3}$$

$$f(x) = \frac{1}{x^2} + \frac{1}{x^3}$$

$$f(x) = \frac{1}{x^2} + \frac{1}{x^3}$$

(2)

$$f(x) = \frac{1}{x^2} + \frac{1}{x^3}$$

$$f(x) = \frac{1}{x^2} + \frac{1}{x^3}$$

(3)

$$f(x) = \frac{1}{x^2} + \frac{1}{x^3}$$

Since ( $N_a \gg N_d$ ), the term  $\frac{N_d}{N_a}$  approaches zero. The depletion region becomes wider as  $N_d$  becomes smaller. Thus by using higher resistivity material the depletion region can be extended. Another means of extending the depletion region is by use of higher reverse bias voltages ( $V_c = V_B + \phi_a - \phi_d$ ).

Since charge must be conserved

$$\begin{aligned} Q_a &= Q_d \\ Q_d &= q N_d d_d \\ &= \left[ \frac{2 \epsilon q N_d V_c}{\left(1 + \frac{N_d}{N_a}\right)} \right]^{\frac{1}{2}} \end{aligned} \quad (A-11)$$

$$\begin{aligned} C = \frac{dQ}{dV} &= \frac{1}{2} \left[ \frac{2 \epsilon q N_d V_c}{1 + \frac{N_d}{N_a}} \right]^{-\frac{1}{2}} \frac{2 \epsilon q N_d}{1 + \frac{N_d}{N_a}} \\ &= \frac{\epsilon q N_d}{1 + \frac{N_d}{N_a}} \left[ \frac{1 + \frac{N_d}{N_a}}{2 \epsilon q N_d V_c} \right]^{\frac{1}{2}} \\ C &= \left[ \frac{\epsilon q N_d}{2 V_c \left(1 + \frac{N_d}{N_a}\right)} \right]^{\frac{1}{2}} = \frac{\epsilon}{d} \end{aligned} \quad (A-12)$$

The expression for capacitance is recognizable as the same as for a parallel plate capacitor and varies directly as the square root of the donor concentration and inversely with the square root of the reverse bias.



Let  $f(x) = x^2 + 1$  and  $g(x) = x^2 - 1$ . Then  $f(x)g(x) = (x^2 + 1)(x^2 - 1) = x^4 - 1$ . The polynomial  $x^4 - 1$  is divisible by  $x^2 + 1$  and  $x^2 - 1$ . The quotient is  $x^2 - 1$  and  $x^2 + 1$  respectively.

$$f(x)g(x) = (x^2 + 1)(x^2 - 1) = x^4 - 1$$

$$f(x) = x^2 + 1$$

$$g(x) = x^2 - 1$$

$$\frac{f(x)g(x)}{f(x)} = \frac{x^4 - 1}{x^2 + 1} = x^2 - 1$$

$$\frac{f(x)g(x)}{g(x)} = \frac{x^4 - 1}{x^2 - 1} = x^2 + 1$$

$$\frac{f(x)g(x)}{f(x)g(x)} = \frac{x^4 - 1}{x^4 - 1} = 1$$

$$f(x)g(x)$$

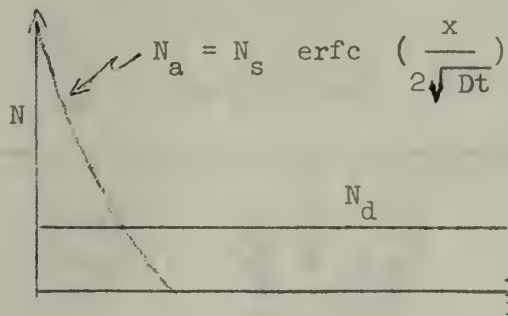
$$\frac{f(x)g(x)}{f(x)g(x)} = 1$$

Let  $f(x) = x^2 + 1$  and  $g(x) = x^2 - 1$ . Then  $f(x)g(x) = (x^2 + 1)(x^2 - 1) = x^4 - 1$ . The polynomial  $x^4 - 1$  is divisible by  $x^2 + 1$  and  $x^2 - 1$ . The quotient is  $x^2 - 1$  and  $x^2 + 1$  respectively.

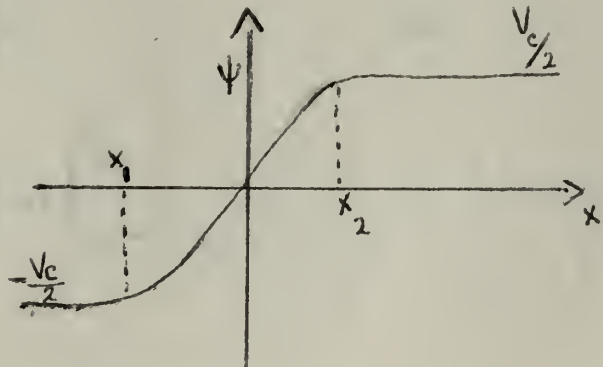
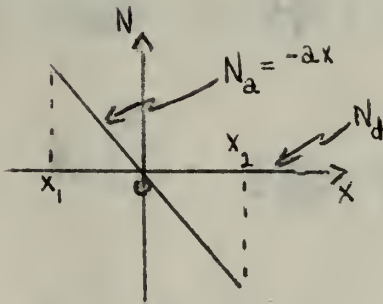
## Appendix B

### Solution of Poisson's Equation for a Graded Junction.

The graded junction solution is applicable to the case of a grown p-n junction or a diffused p-n junction when the diffusion is carried out over a relatively long period of time.



The equation for  $N_a$  is the solution of the diffusion equation for a constant surface source. As a first approximation it can be assumed that  $N_a$  is a straight line in the vicinity where it crosses  $N_d$



### Boundary Conditions

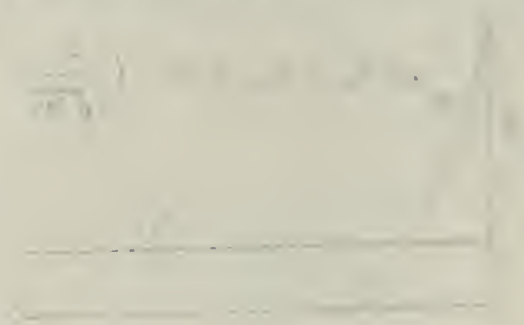
$$\left. \frac{d\psi_a}{dx} \right|_{x=x_1} = 0$$

$$\left. \frac{d\psi_d}{dx} \right|_{x=x_2} = 0$$

# PROBLEM 1

Consider the function  $f(x) = \sin(x)$  defined on the interval  $[0, 2\pi]$ .

(a) Find the maximum and minimum values of  $f(x)$  on the interval  $[0, 2\pi]$ .  
 (b) Find the points on the graph of  $f(x)$  where the tangent line is horizontal.



(c) Find the area under the curve  $f(x) = \sin(x)$  from  $x = 0$  to  $x = \pi$ .  
 (d) Find the average value of  $f(x)$  on the interval  $[0, 2\pi]$ .



$$f(x) = \sin(x)$$

$$f'(x) = \cos(x)$$

$$\psi_a \Big|_{x=x_1} = -\frac{V_c}{2}$$

$$\psi_d \Big|_{x=x_2} = \frac{V_c}{2}$$

$$\psi_1 = \psi_2 \text{ at } x = 0$$

$$x_1 = -x_2$$

$$N_a = -ax$$

$$\rho_a = -q N_a = q ax$$

$$\frac{d^2 \psi_a}{dx^2} = -\frac{\rho_a}{\epsilon} = -\frac{q ax}{\epsilon}$$

$$\frac{d \psi_a}{dx} \Big|_{x_1}^x = -\frac{q a}{\epsilon} \frac{x^2}{2} \Big|_{x_1}^x$$

$$\frac{d \psi_a}{dx} = -\frac{q a}{2 \epsilon} (x^2 - x_1^2) \quad (B-1)$$

$$\psi_a \Big|_{x_1}^{x_2} = -\frac{q a}{2 \epsilon} \left( \frac{x^3}{3} - x_1^2 x \right) \Big|_{x_1}^{x_2} = -x_2$$

$$V_c = \frac{q a}{2 \epsilon} \frac{4}{3} x_2^3$$

$$x_2 = \left[ \frac{3 \epsilon V_c}{2 q a} \right]^{1/3}$$

$$d = 2 x_2 = \left[ \frac{12 \epsilon V_c}{q a} \right]^{1/3} \quad (B-2)$$

$$4 - 2 \frac{1}{2} \frac{1}{2} \frac{1}{2}$$

$$2 \frac{1}{2} \frac{1}{2} \frac{1}{2}$$

$$2 \frac{1}{2} \frac{1}{2} \frac{1}{2}$$

$$2 \frac{1}{2} \frac{1}{2} \frac{1}{2}$$

$$2 \frac{1}{2} \frac{1}{2} \frac{1}{2}$$

$$2 \frac{1}{2} \frac{1}{2} \frac{1}{2}$$

$$2 \frac{1}{2} \frac{1}{2} \frac{1}{2}$$

$$2 \frac{1}{2} \frac{1}{2} \frac{1}{2}$$

$$(2-4)$$

$$(2-4) \frac{1}{2} \frac{1}{2} \frac{1}{2}$$

$$(2-4) \frac{1}{2} \frac{1}{2} \frac{1}{2}$$

$$(2-4) \frac{1}{2} \frac{1}{2} \frac{1}{2}$$

$$(2-4) \frac{1}{2} \frac{1}{2} \frac{1}{2}$$

$$(2-4) \frac{1}{2} \frac{1}{2} \frac{1}{2}$$

$$(2-4)$$

Equation (B-2) shows that the depletion region varies directly with the cube root of the applied reverse bias.

$$C = \frac{dQ}{dV}$$

$$dQ_a = -q N_a dx = q a x dx$$

$$Q_a \Big|_0^{x=x_2} = \frac{q a x^2}{2} \Big|_0^{x=x_2}$$

$$Q_a = \frac{q a x_2^2}{2} = \frac{q a}{2} \left[ \frac{3 \epsilon V_c}{2 q a} \right]^{2/3}$$

$$\frac{dQ_a}{dV} = C = \frac{\epsilon}{2 \left[ \frac{3 \epsilon V_c}{2 q a} \right]^{1/3}} = \frac{\epsilon}{d} \quad (B-3)$$

Equation (B-3) is the equation of a parallel plate capacitor and it shows that the capacitance varies inversely with the cube root of the applied reverse bias.



the generalization of the result obtained for the case  $p=1$  and  $q=1$  to the case  $p=1$  and  $q=2$  is given by the following theorem.

$$\frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-\frac{1}{2}x^2} dx = 1$$

$$x^2 + y^2 = 1 \Rightarrow x^2 = 1 - y^2 \Rightarrow x = \pm \sqrt{1 - y^2}$$

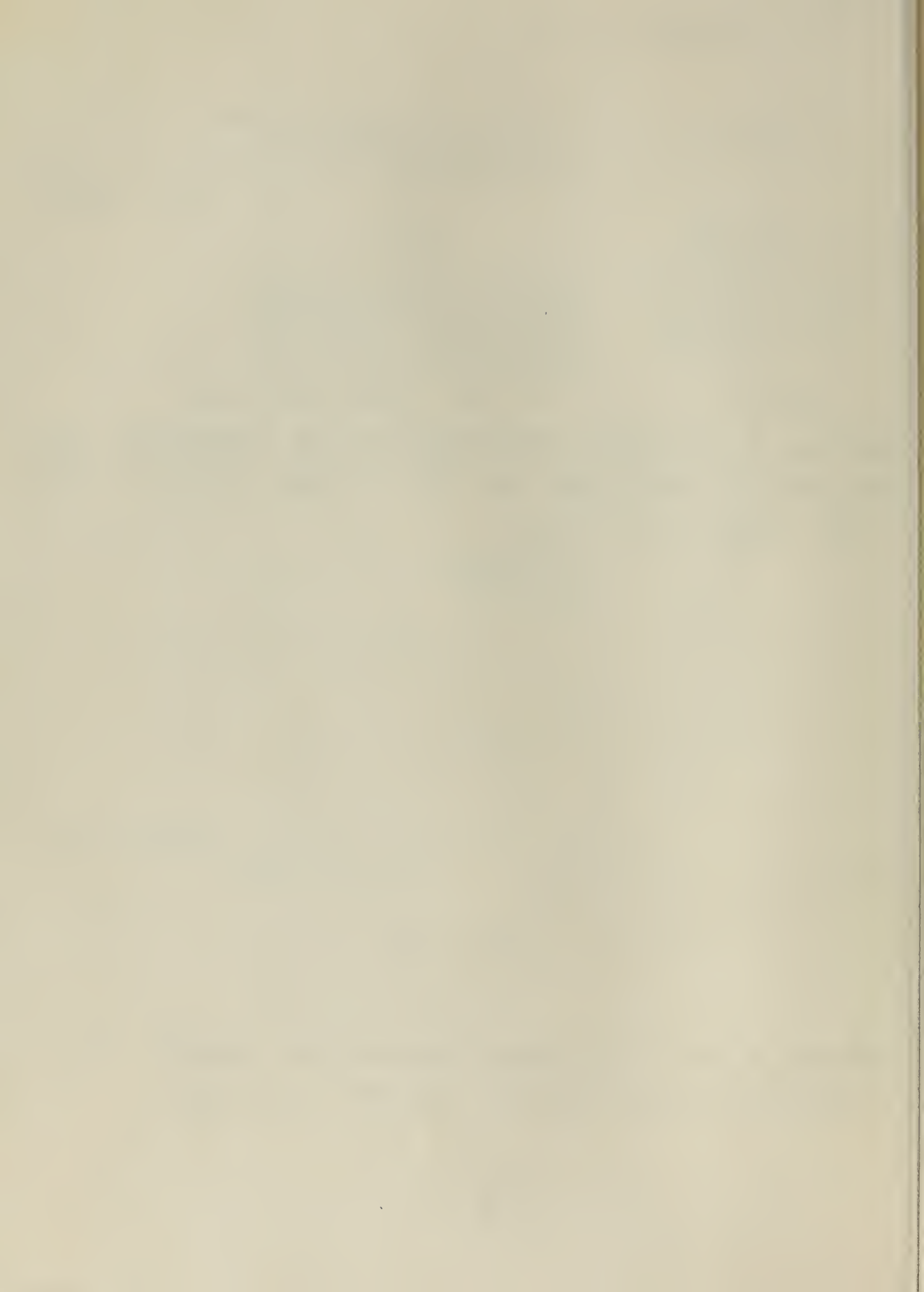
$$\int_{-\sqrt{1-y^2}}^{\sqrt{1-y^2}} dx = 2\sqrt{1-y^2}$$

$$\int_{-\infty}^{\infty} \left[ \frac{1}{\sqrt{1-y^2}} \right] dy = \frac{2}{\sqrt{1-y^2}} = 2$$

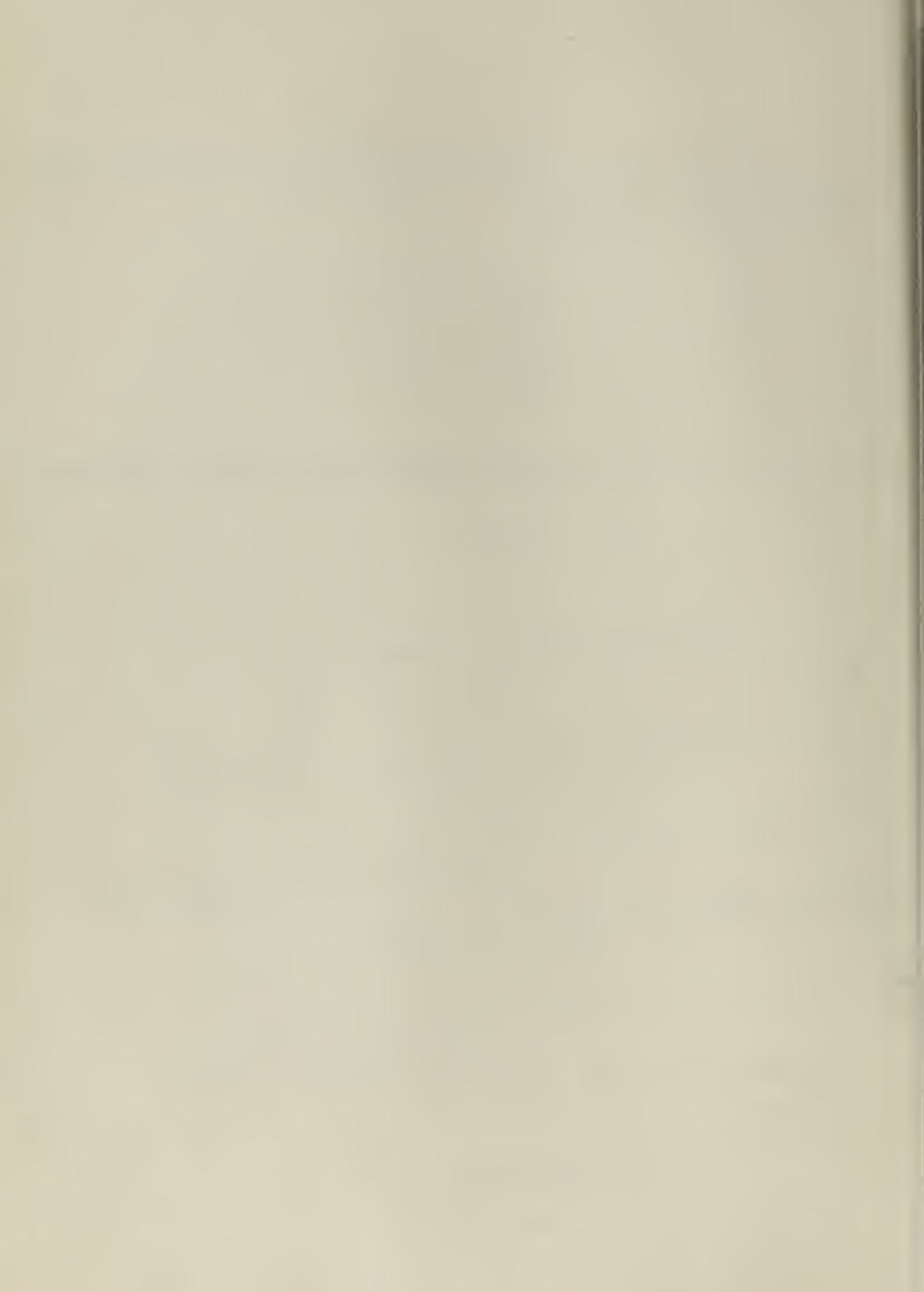
$$(4-3) \quad \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-\frac{1}{2}x^2} dx = 1 \Rightarrow \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-\frac{1}{2}x^2} dx = 1$$

It has been shown that the integral (4-3) is equal to 1. This result is used in the proof of the central limit theorem. The following theorem is a generalization of the result obtained for the case  $p=1$  and  $q=1$  to the case  $p=1$  and  $q=2$ .









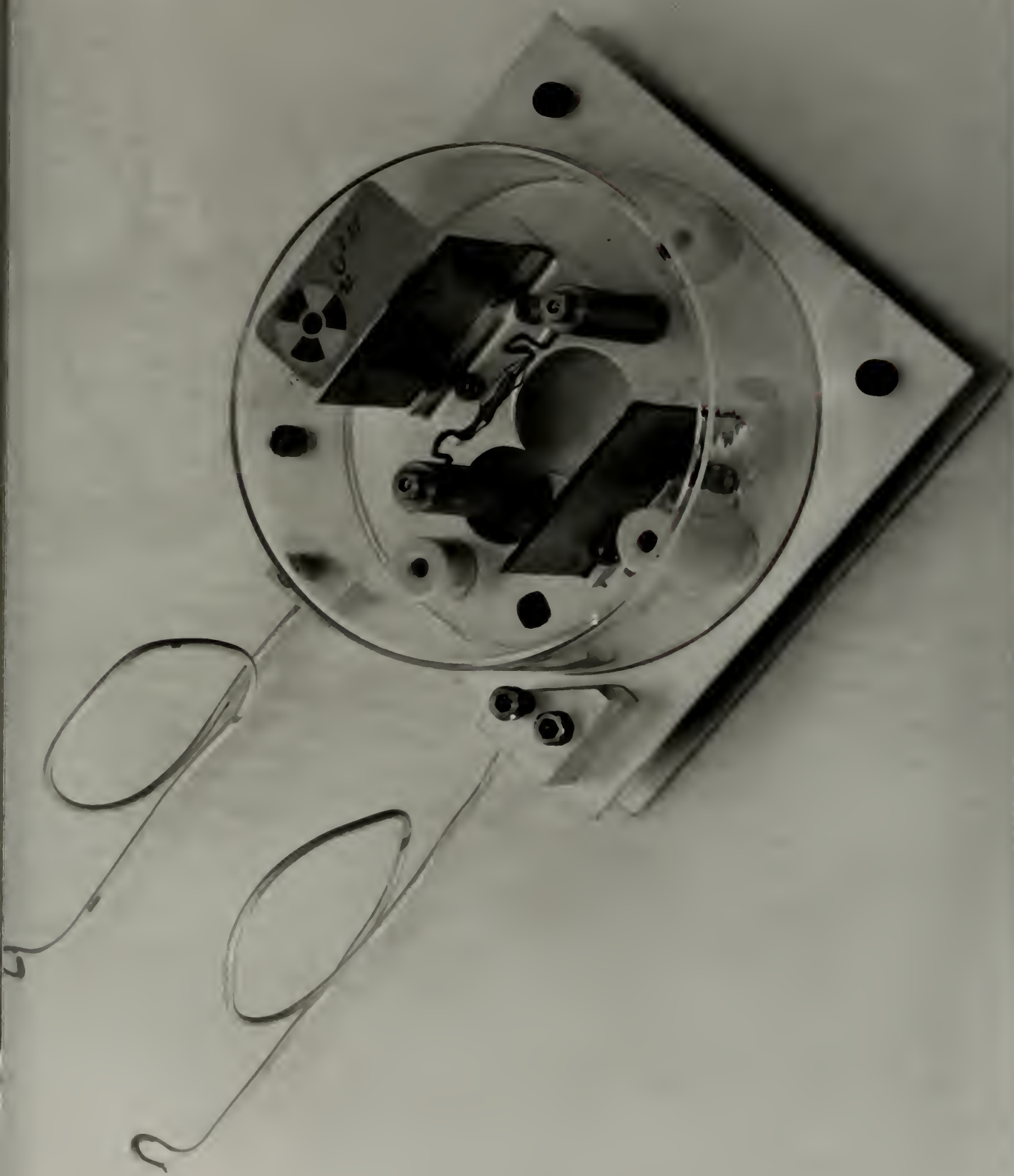


Figure 5 - Uranium evaporation jig



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Figure 6 - Filament detail

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Figure 7 - Vacuum chamber

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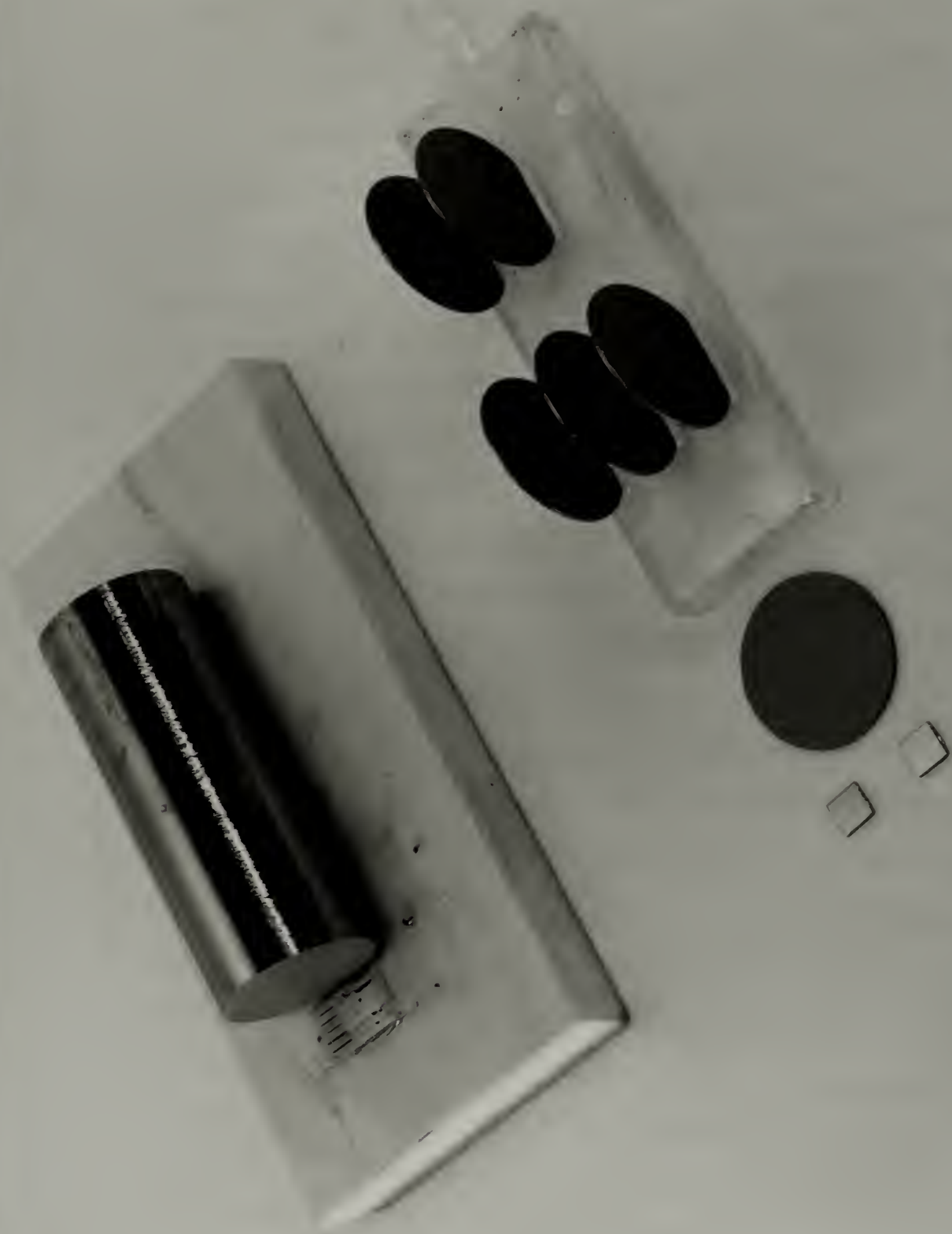


Figure 2 - Si in single crystal, silicon slices and quartz holder



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Figure 10 to be included in UCRL report.

1914

1914

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Figure 11 - Diffusion furnace



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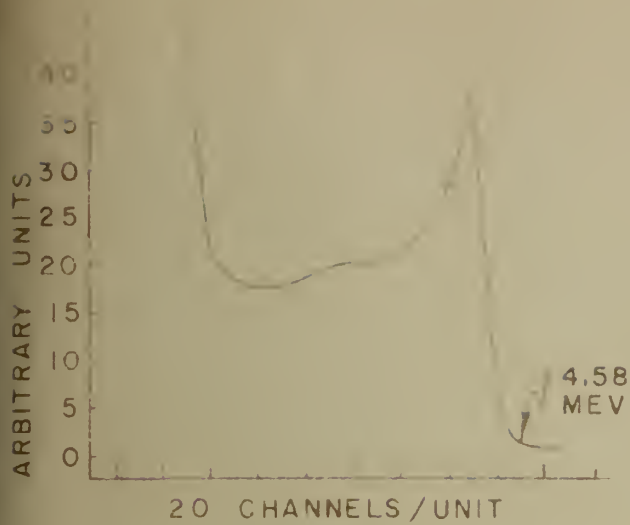


Fig. 12

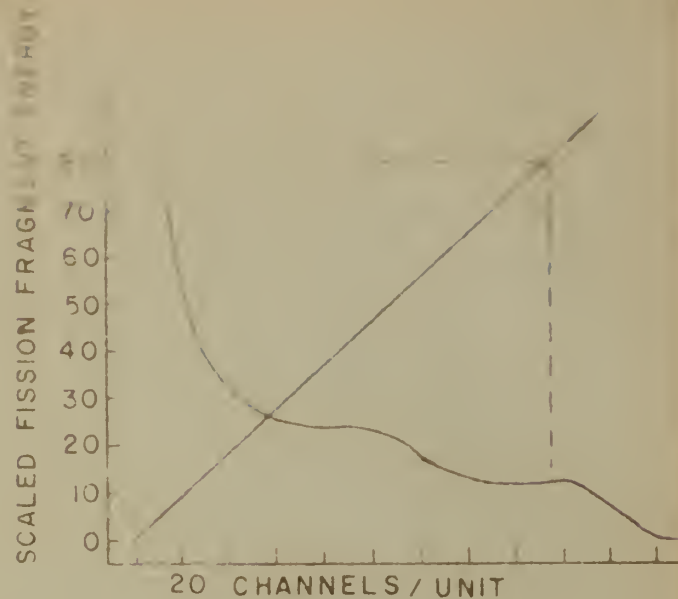
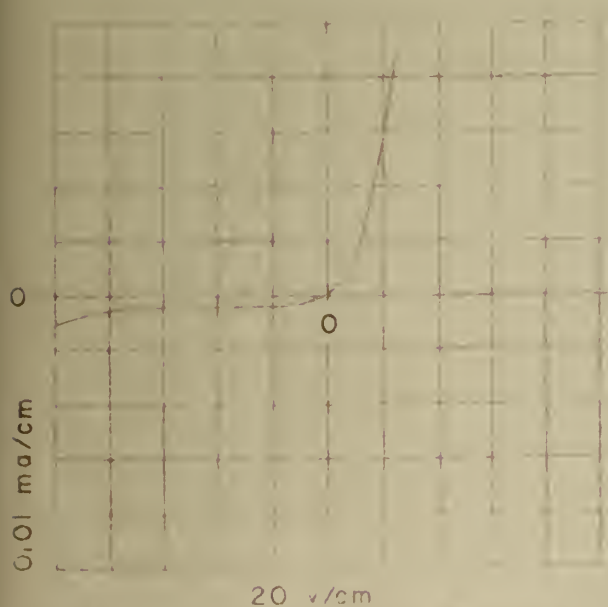
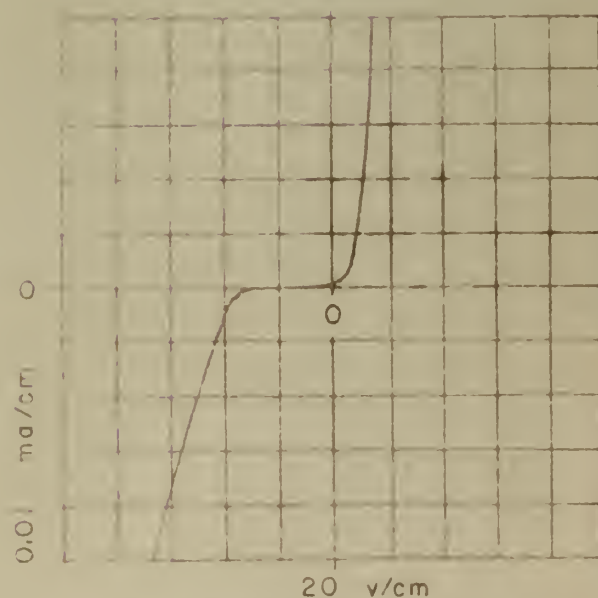


Fig. 13



DIODE CHARACTERISTICS OF THE URANIUM COATED, OXIDE SURFACE BARRIER DETECTOR.

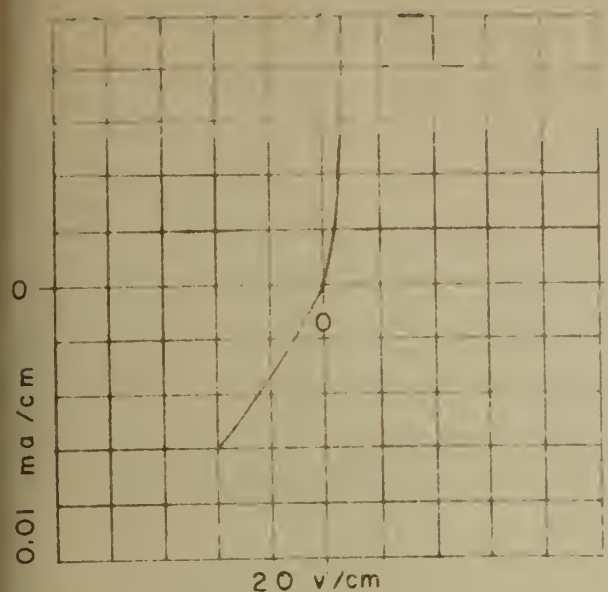
Fig. 14



DIODE CHARACTERISTICS OF THE URANIUM COATED, FRESHLY ETCHED SURFACE BARRIER DETECTOR.

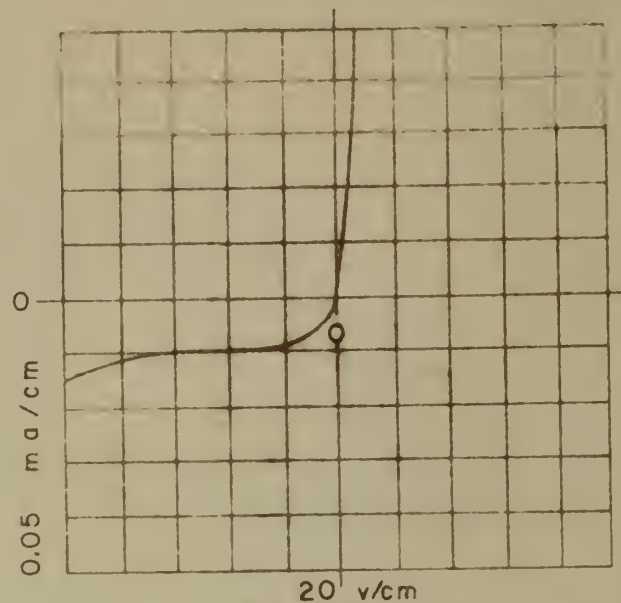
Fig. 15





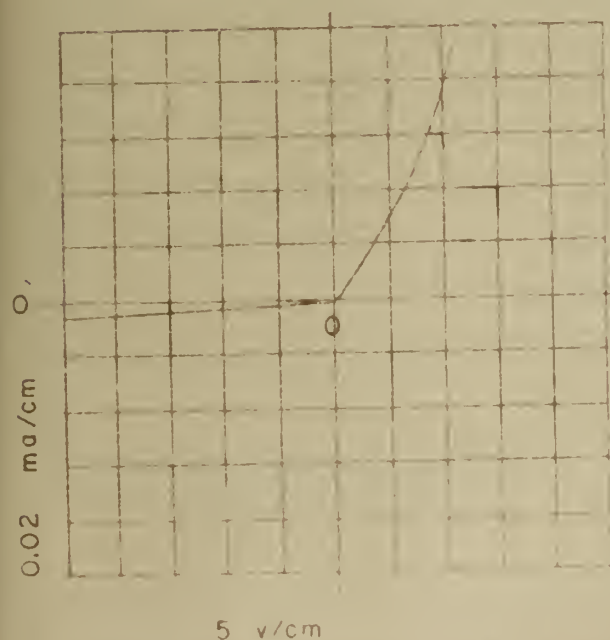
DIODE CHARACTERISTICS OF THE  
URANIUM COATED, BORON DIFFUSED  
DETECTOR.

Fig. 16



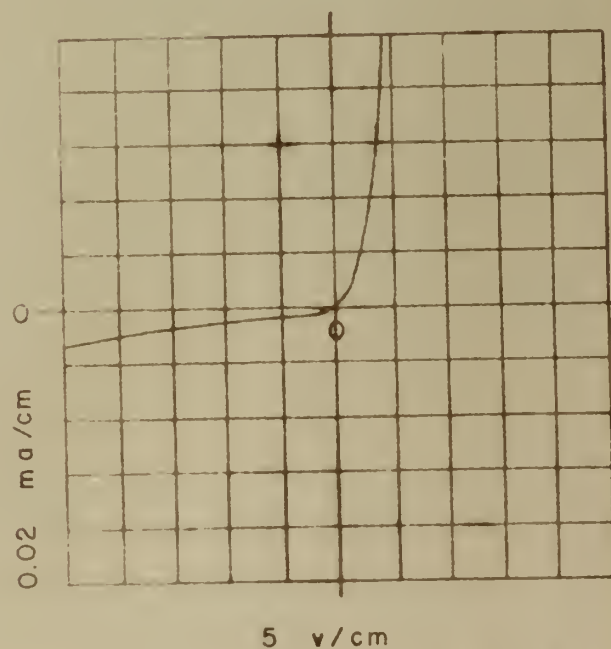
DIODE CHARACTERISTICS OF THE  
URANIUM & GOLD COATED SURFACE  
BARRIER DETECTOR.

Fig. 17



DIODE CHARACTERISTICS OF A BORON-10  
PAINTED, BORON DIFFUSED DETECTOR.

Fig. 18



DIODE CHARACTERISTICS OF A  
BORON-10 DIFFUSED DETECTOR.

Fig. 19





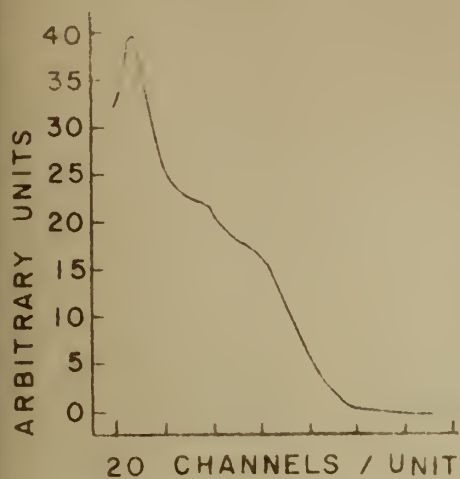


Fig. 20

BORON-10 REACTION PARTICLE SPECTRUM,  
0 VOLTS REVERSE BIAS.

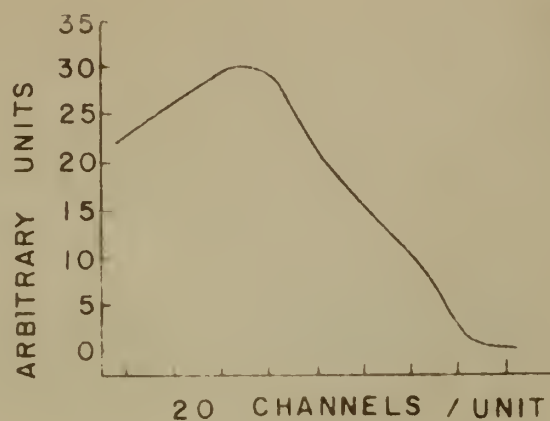


Fig. 21

BORON-10 REACTION PARTICLE SPECTRUM,  
5 VOLTS REVERSE BIAS.

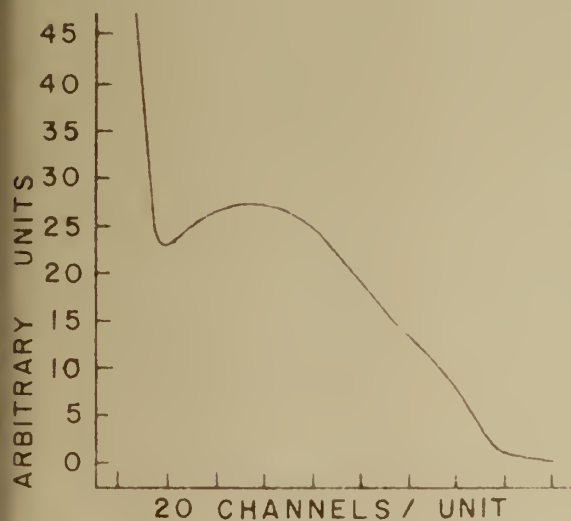
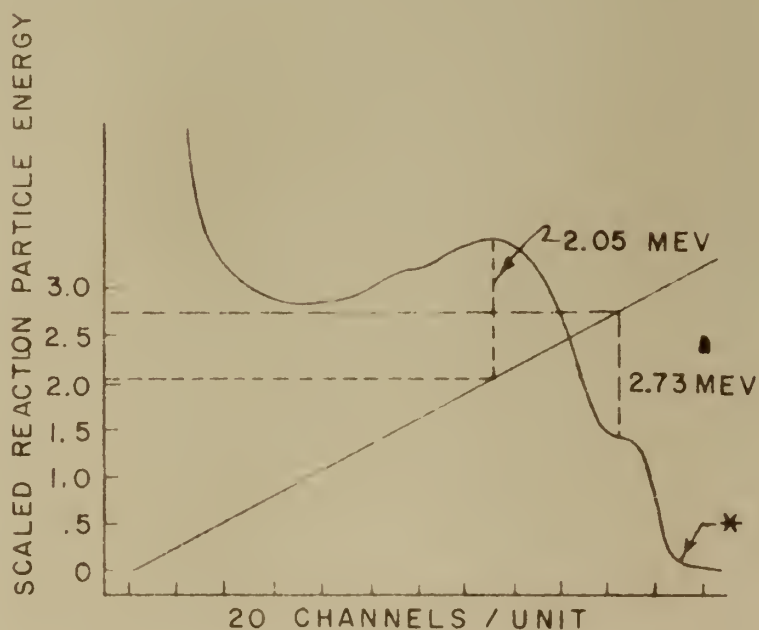


Fig. 22

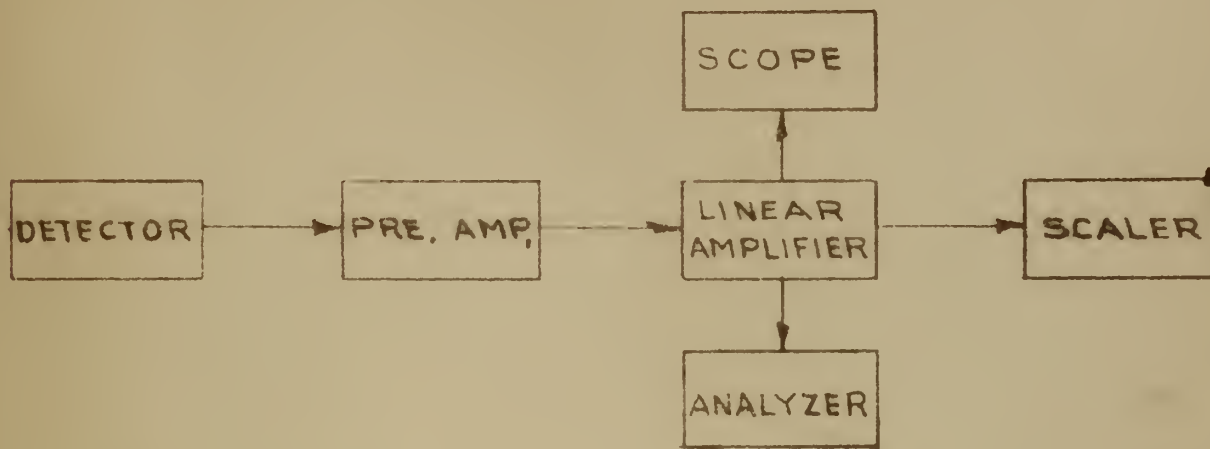
BORON-10 REACTION PARTICLE SPECTRUM,  
10 VOLTS REVERSE BIAS.



\* MAXIMUM ENERGY OF TRITON  
Fig. 23

LITHIUM-6 REACTION PARTICLE SPECTRUM,  
10 VOLTS REVERSE BIAS.





## ELECTRONICS TEST EQUIPMENT

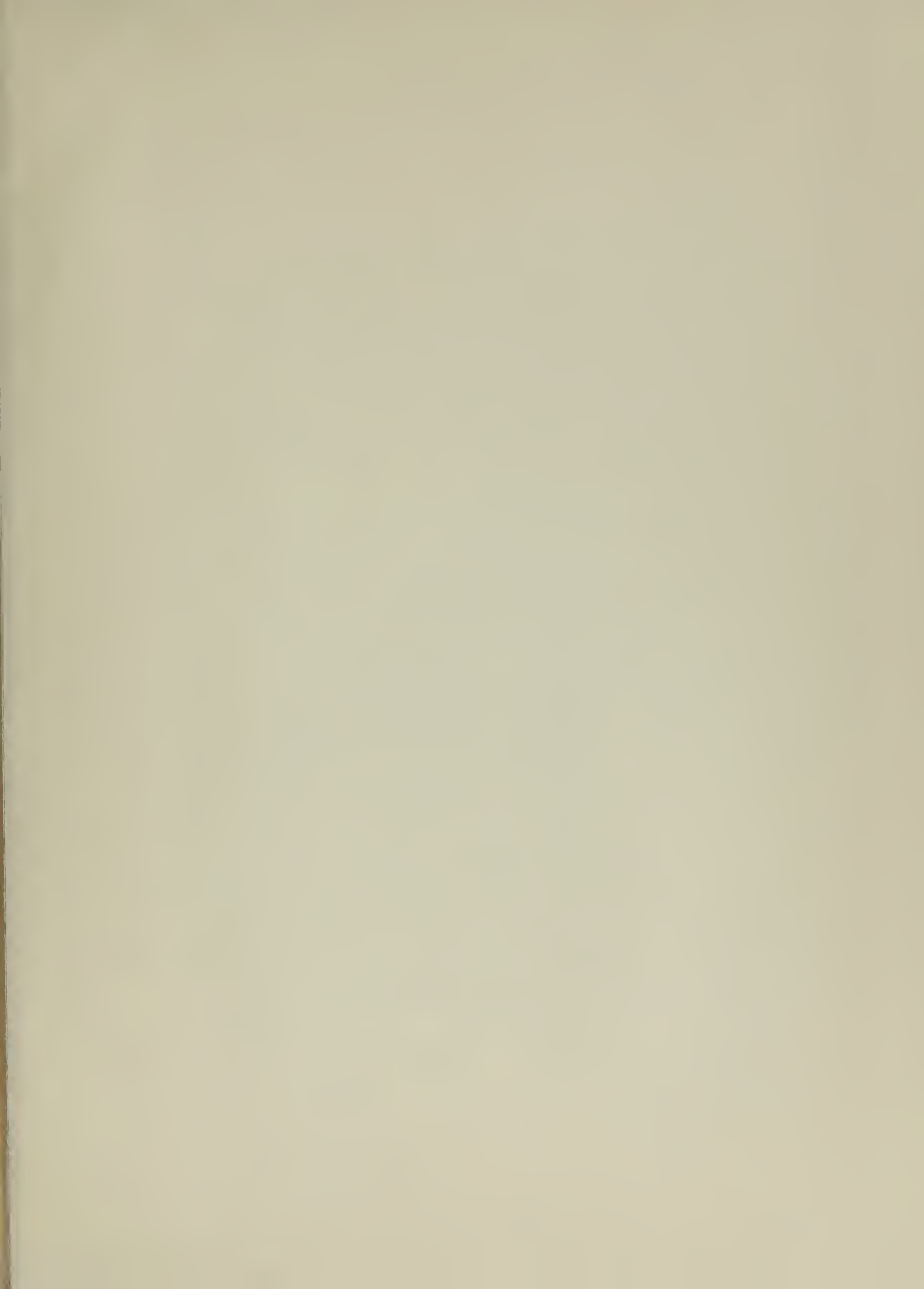
Fig. 24









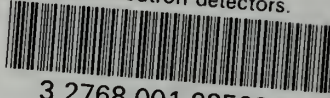






thesM965

Solid state neutron detectors.



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